Initial geometry fluctuations
and
Triangular flow

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MIT

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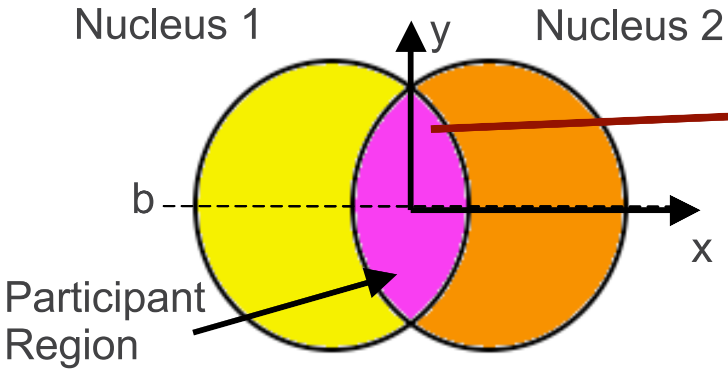
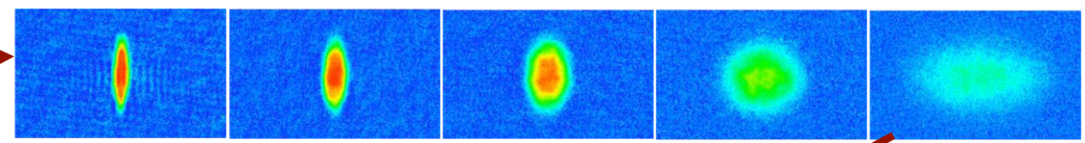
BA, G.Roland, PRC81, 054905 (2010)

Traditional picture

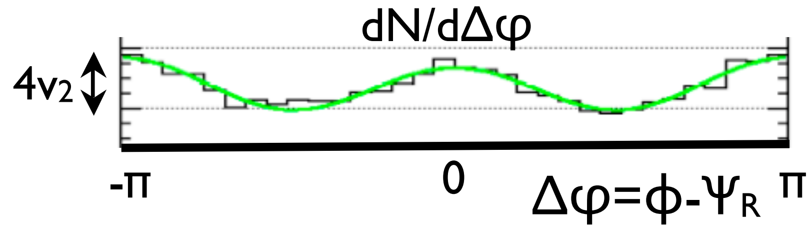
Initial anisotropy



Pressure driven expansion



Final anisotropy

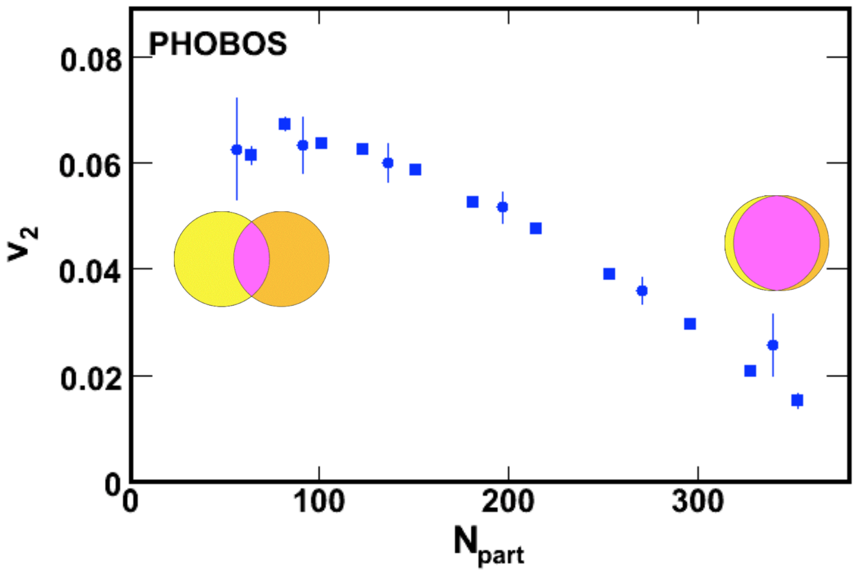


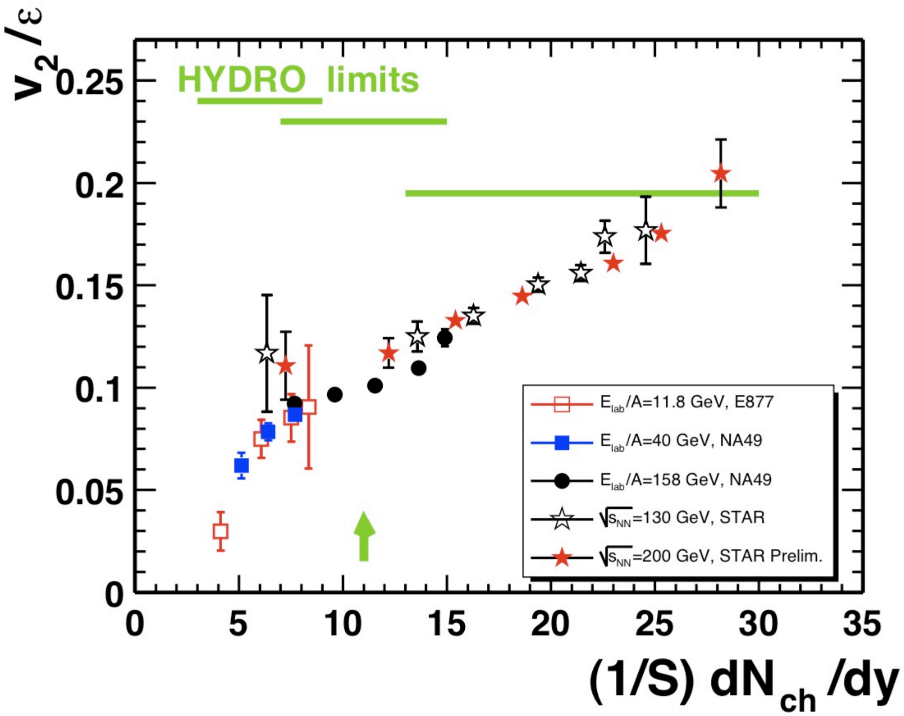
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \underline{\psi_R})\right)\right\rangle \propto \varepsilon$$

Elliptic flow is quantified by the second Fourier coefficient (v_2) of the observed particle distribution

"The Perfect Liquid at RHIC"



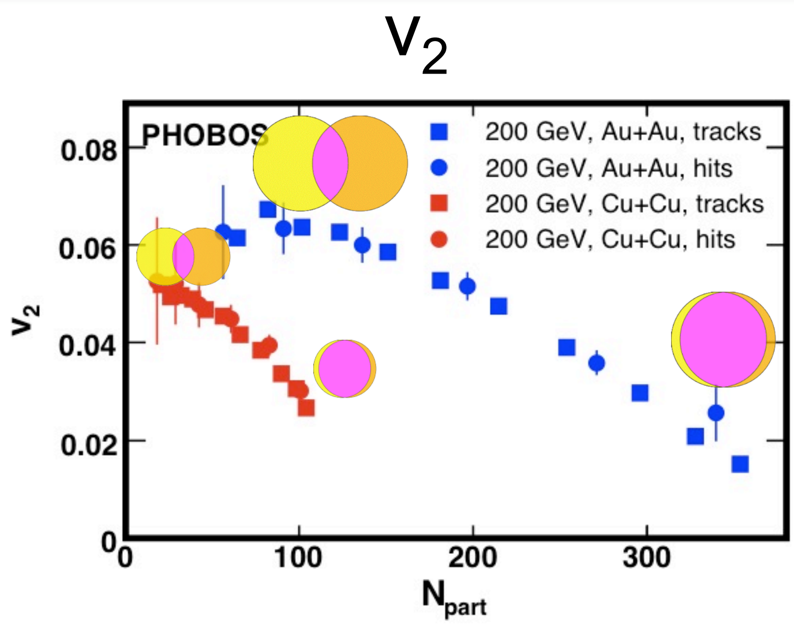


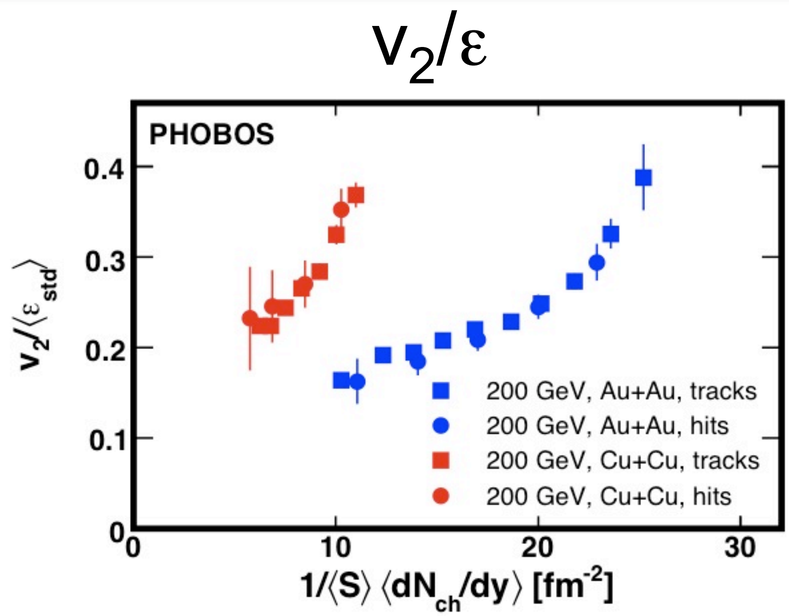
Large elliptic flow signal at RHIC suggests early thermalization and strongly interacting medium

PHOBOS PRC72, 051901 (2005)

NA49 PRC68 034903 (2003)

Elliptic flow in Cu+Cu collisions





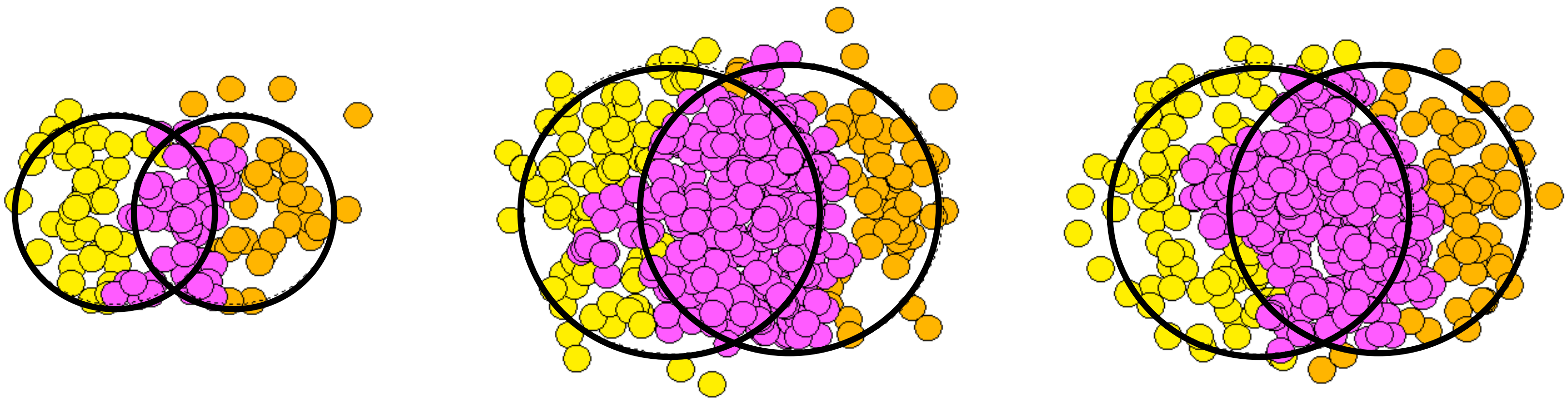
Elliptic flow signal in Cu+Cu collisions was observed to be surprisingly large, in particular for the most central collisions

PHOBOS PRL 98, 242302 (2007)

Initial geometry

Glauber Model Description of the initial geometry:

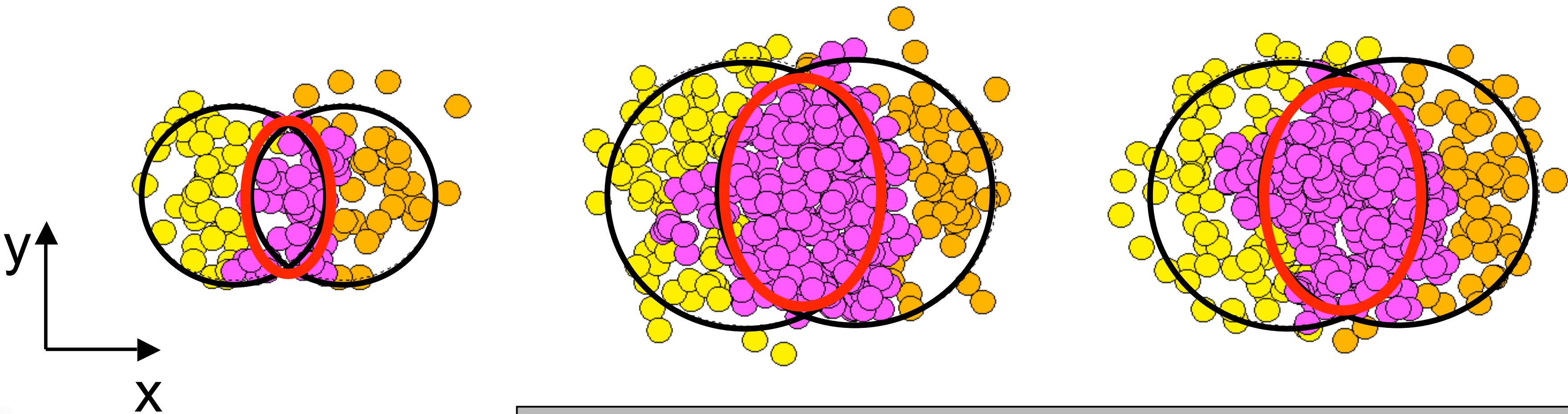
- Nuclei consist of randomly positioned nucleons
- Impact parameter is randomly selected
- Nucleons collide if closer than $D = \sqrt{\sigma_{NN}/\pi}$



PHOBOS PRL 98, 242302 (2007)

“Standard” eccentricity

Eccentricity of the collision region
can be calculated from positions of nucleons



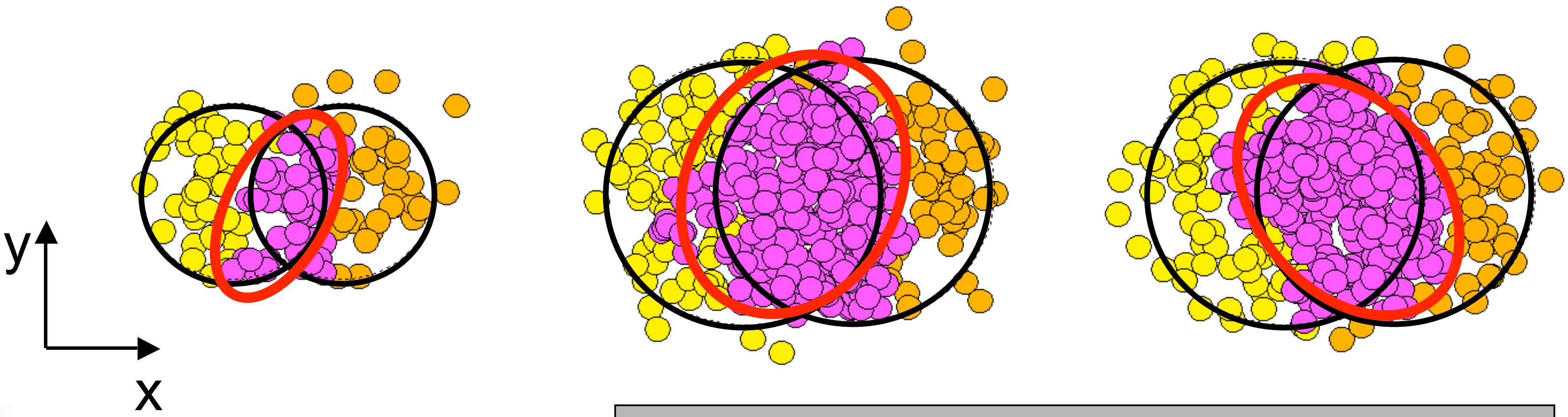
$$\varepsilon_{\mathbf{RP}} = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Underlying assumption:
Event-by-event fluctuations in
Glauber model are not physical

PHOBOS PRL 98, 242302 (2007)

“Participant” eccentricity

Eccentricity of the collision region
can be calculated from positions of nucleons

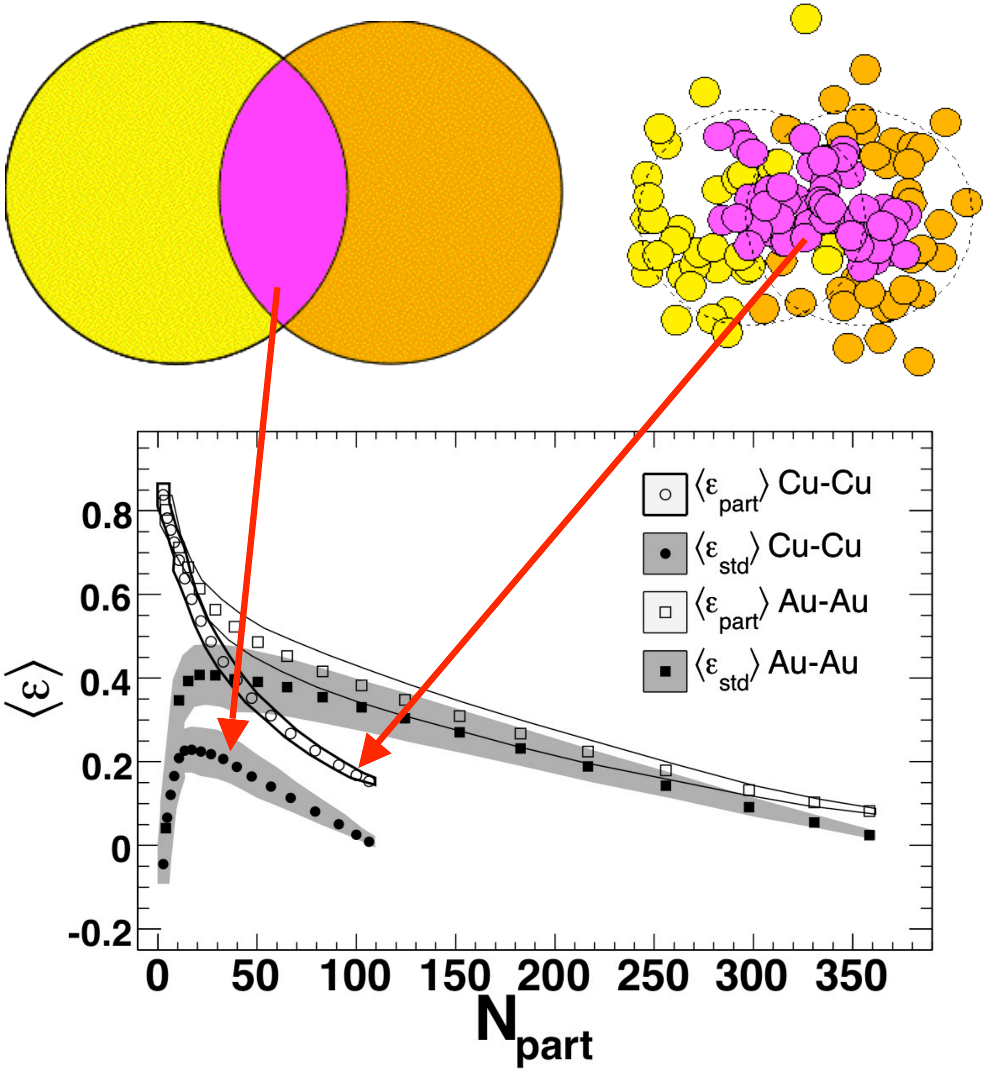


$$\varepsilon_{\mathbf{part}} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

Participant eccentricity is
calculated with no reference
to the impact parameter vector

PHOBOS PRL 98, 242302 (2007)

Two different pictures

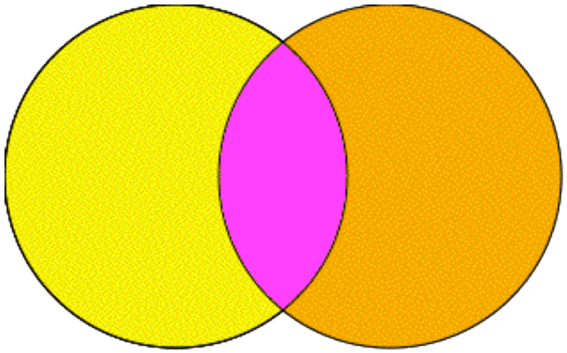


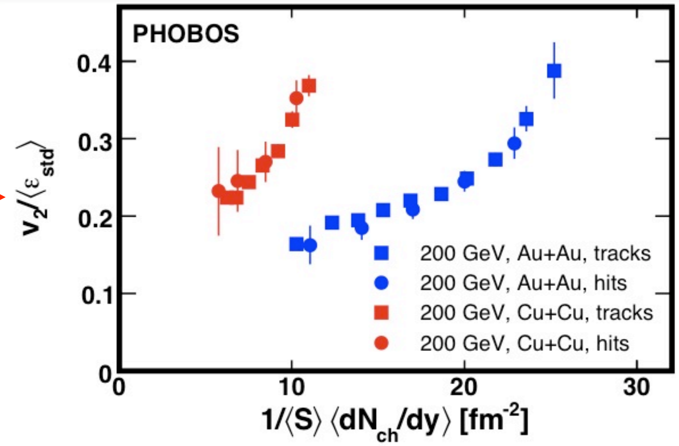
Participant eccentricity is finite even for most central collisions.

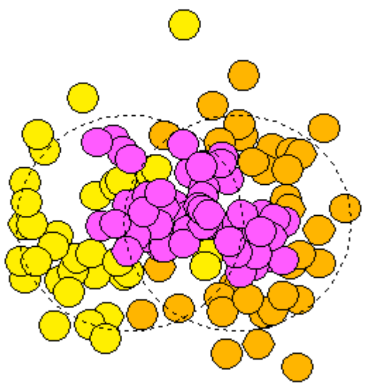
A greater impact on the smaller Cu+Cu system

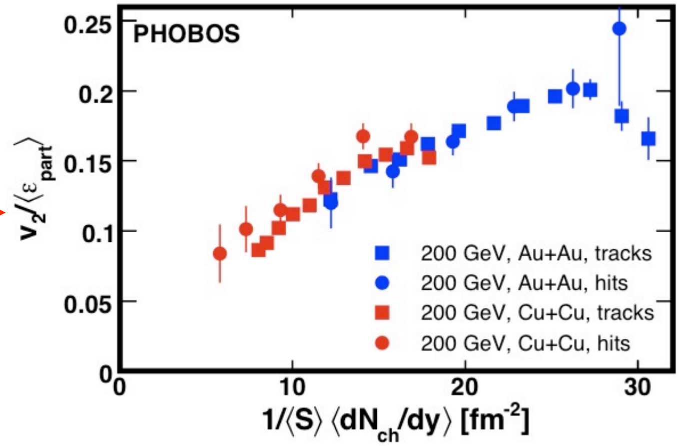
PHOBOS PRL 98, 242302 (2007)

Two different pictures







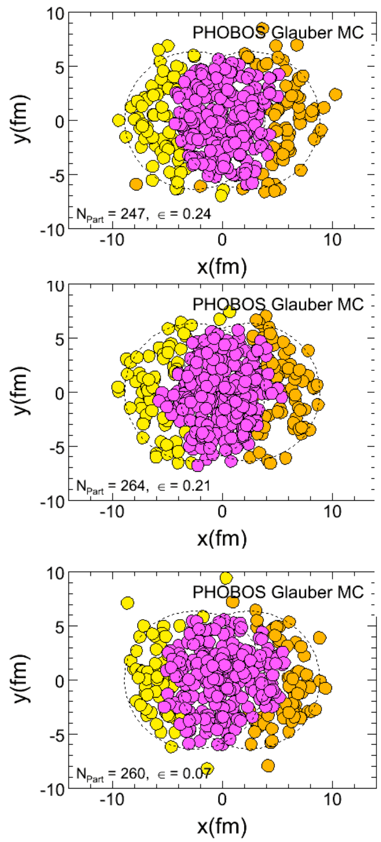


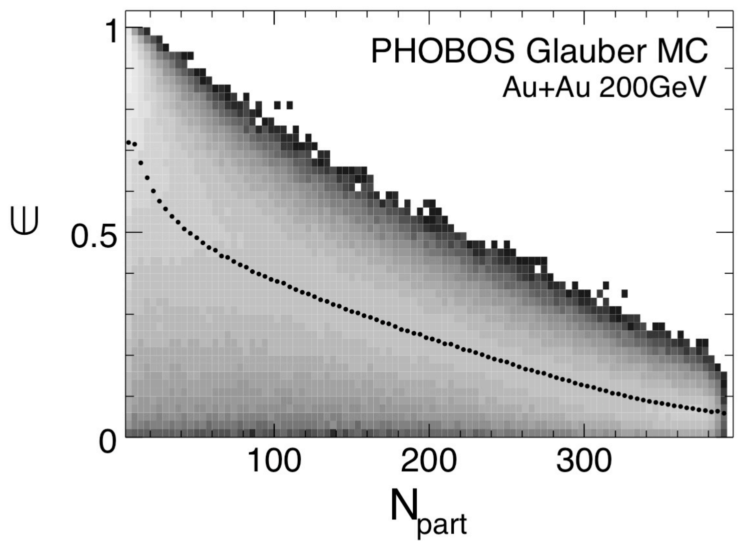
Participant eccentricity reconciles
elliptic flow for Cu+Cu and Au+Au collisions

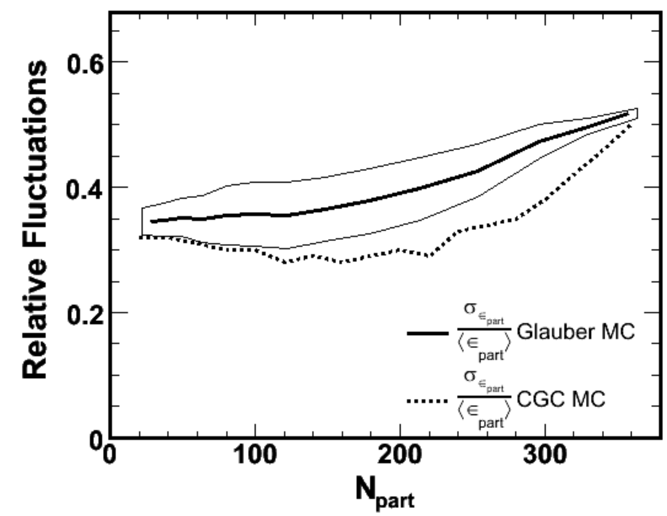
PHOBOS PRL 98, 242302 (2007)

Elliptic flow fluctuations

If initial geometry fluctuations are present
v_2 should fluctuate event-by-event
at fixed N_{part} or b

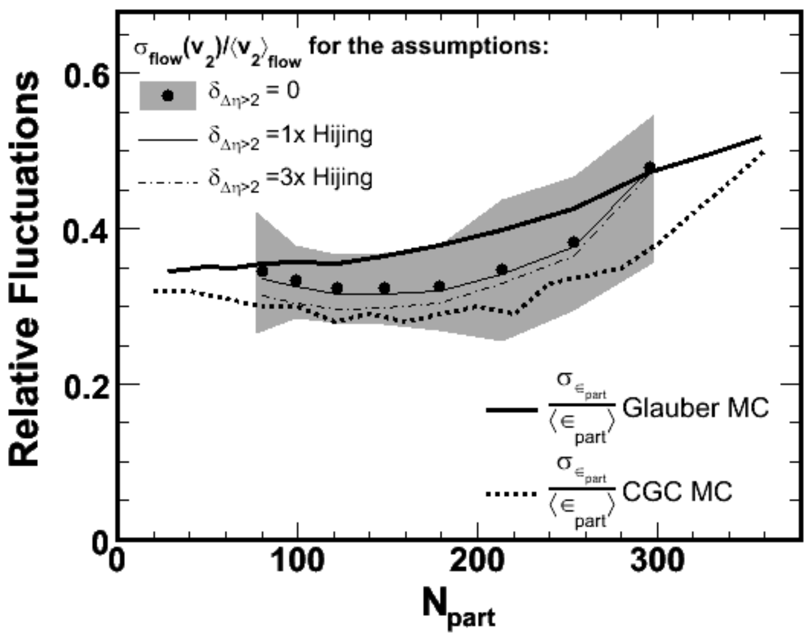






Elliptic flow fluctuations

As predicted
v_2 fluctuates event-by-event
at fixed N_{part}

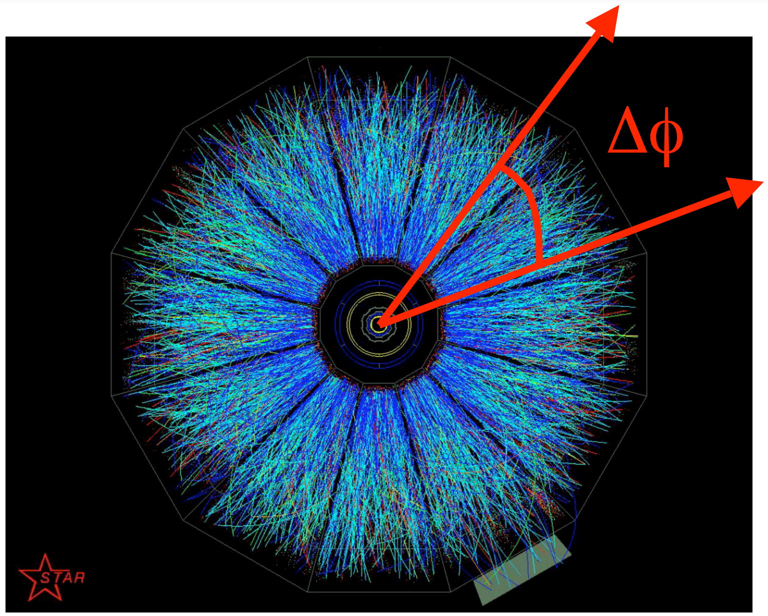


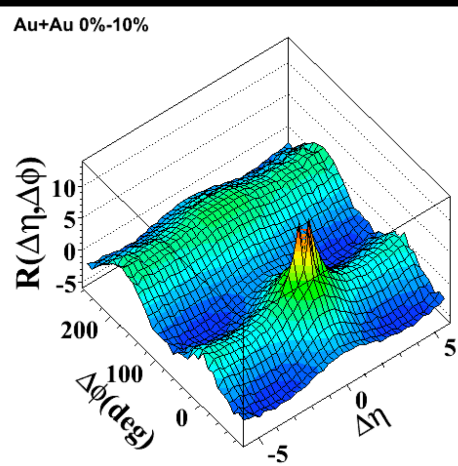
Statistical fluctuations and non-flow correlations are taken out in these results.

CGC: Drescher, Nara, PRC C76, 041903 (2007)

PHOBOS PRL 104, 142301 (2010)
PHOBOS PRC81, 034915 (2010)

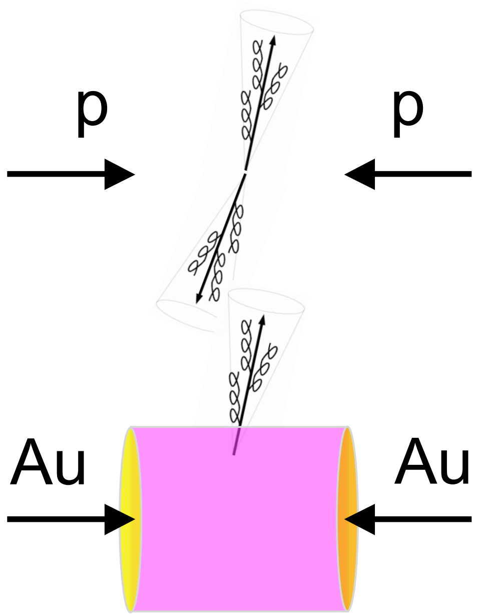
Two-particle correlations

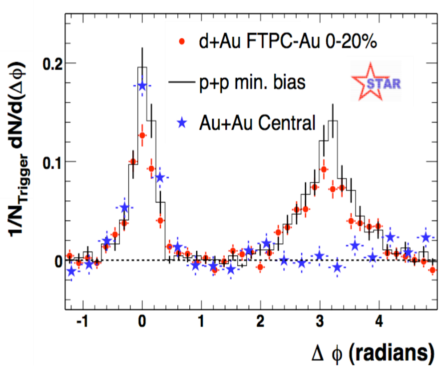


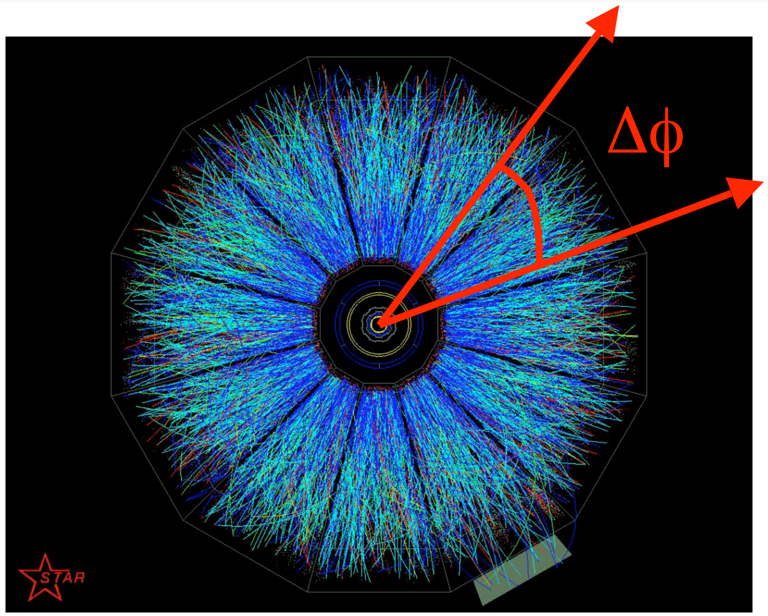


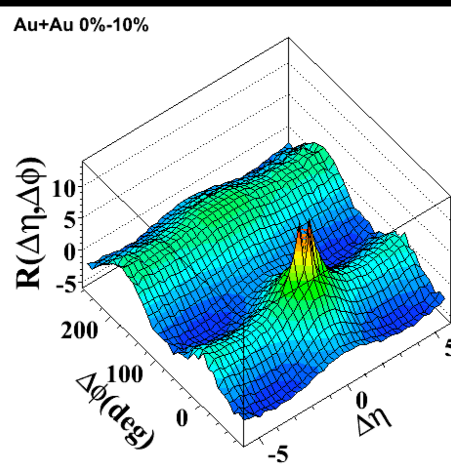
Two-particle correlations

Non-flow

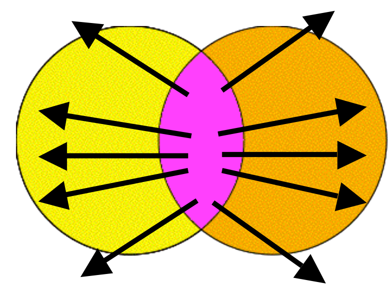


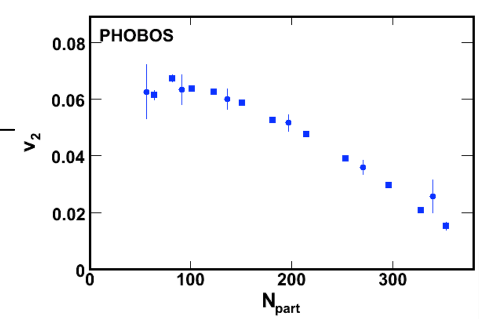




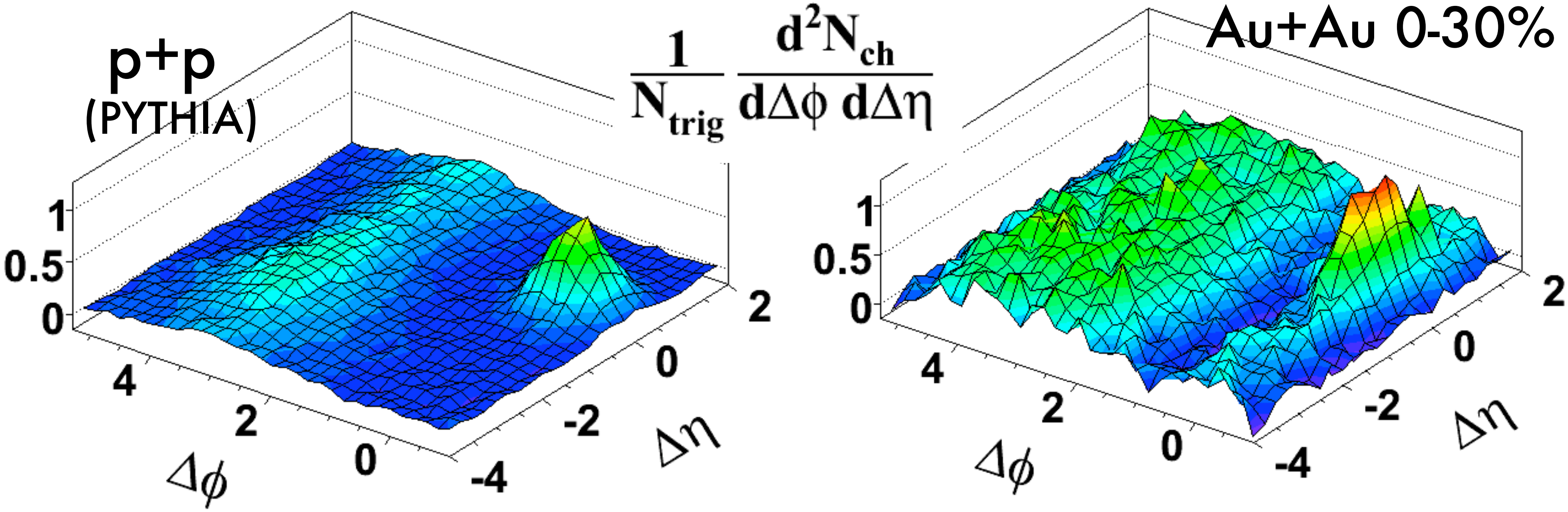


Flow





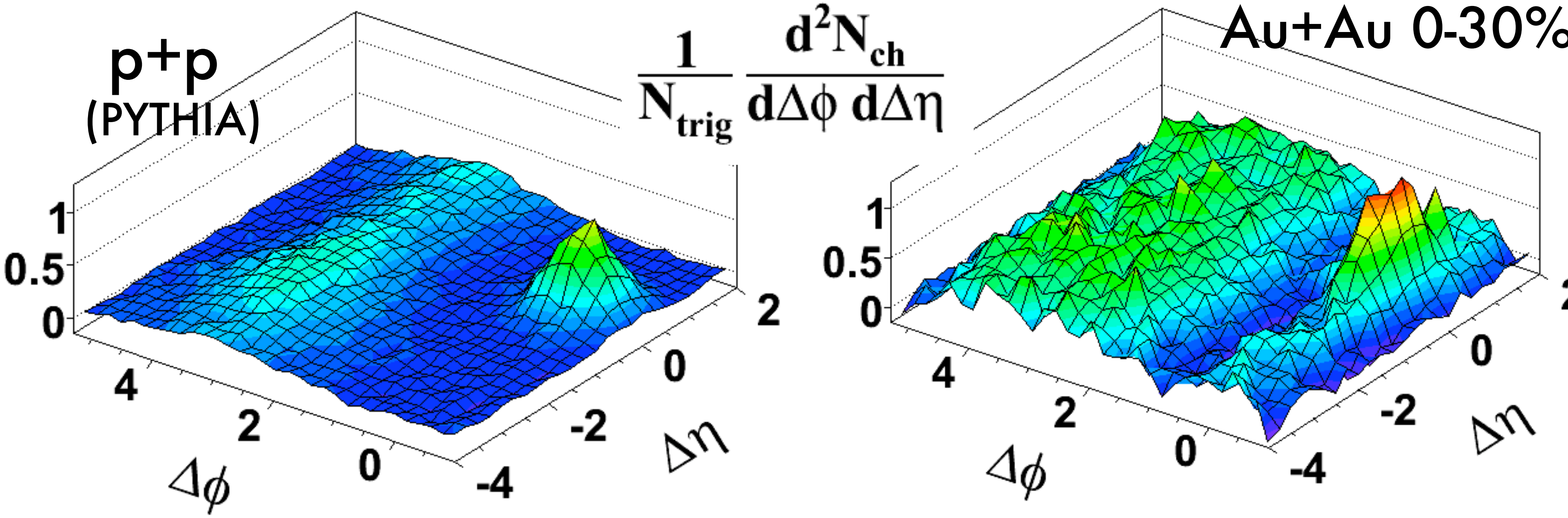
Ridge and Broad Away side

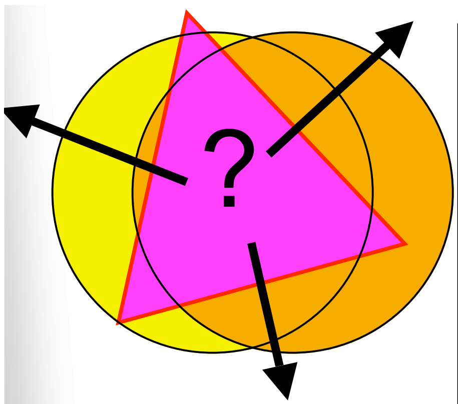


A large correlation structure at $\Delta\phi$=0°
and a broad away side at $\Delta\phi$=180°
is observed out to $\Delta\eta$=4

PHOBOS PRL 104, 06230 (2010)

High p_T triggered correlations





Collective Flow?

- Triangular anisotropy in initial geometry
- Description of data in terms of triangular flow
- Model description of triangular anisotropy

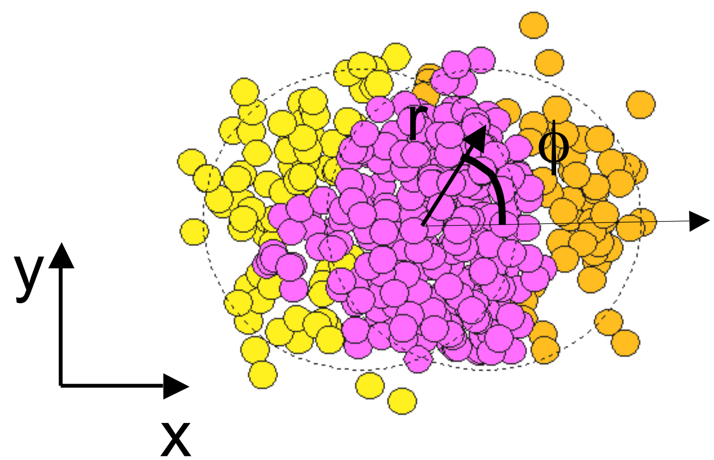
PHOBOS PRL 104, 06230 (2010)

BA, G.Roland, PRC81, 054905 (2010)

Participant triangularity

Triangular anisotropy in initial geometry can be quantified by “participant triangularity” analogous to participant eccentricity.

$$\varepsilon = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



$$\varepsilon = \frac{\sqrt{\left\langle \left(r^2 \cos(2\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(2\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

BA, G.Roland, PRC81, 054905 (2010)

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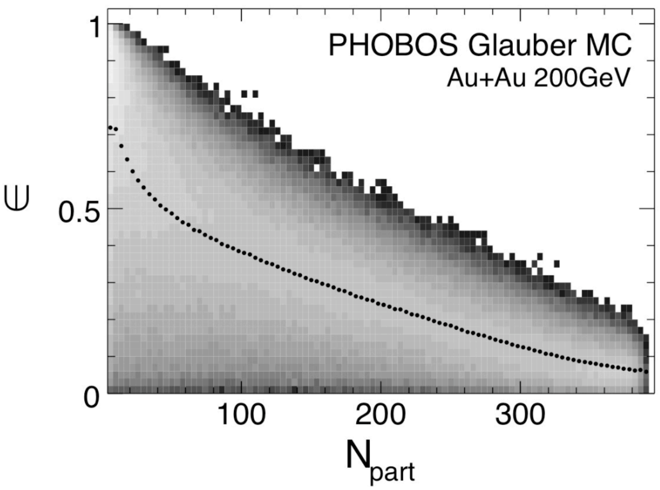
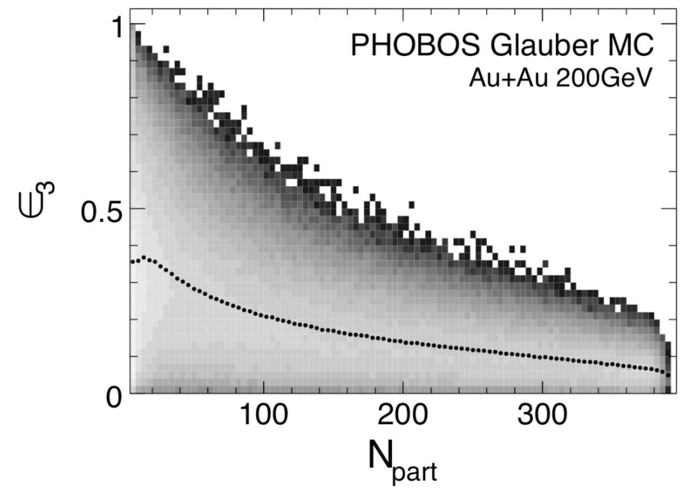
$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$





BA, G.Roland, PRC81, 054905 (2010)

Participant triangularity

Triangular anisotropy in initial geometry
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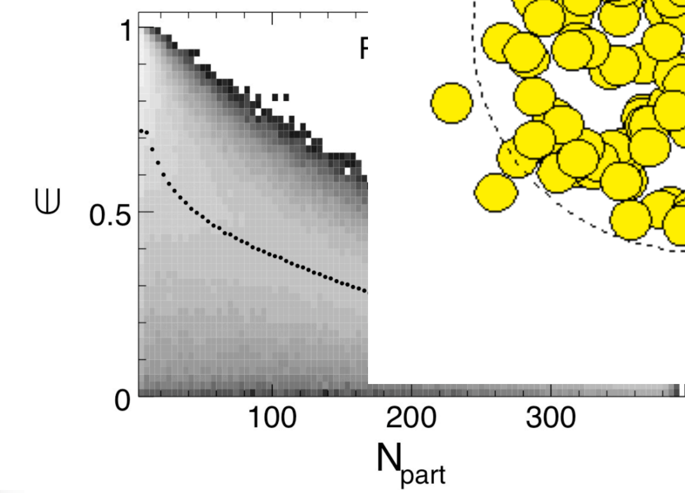
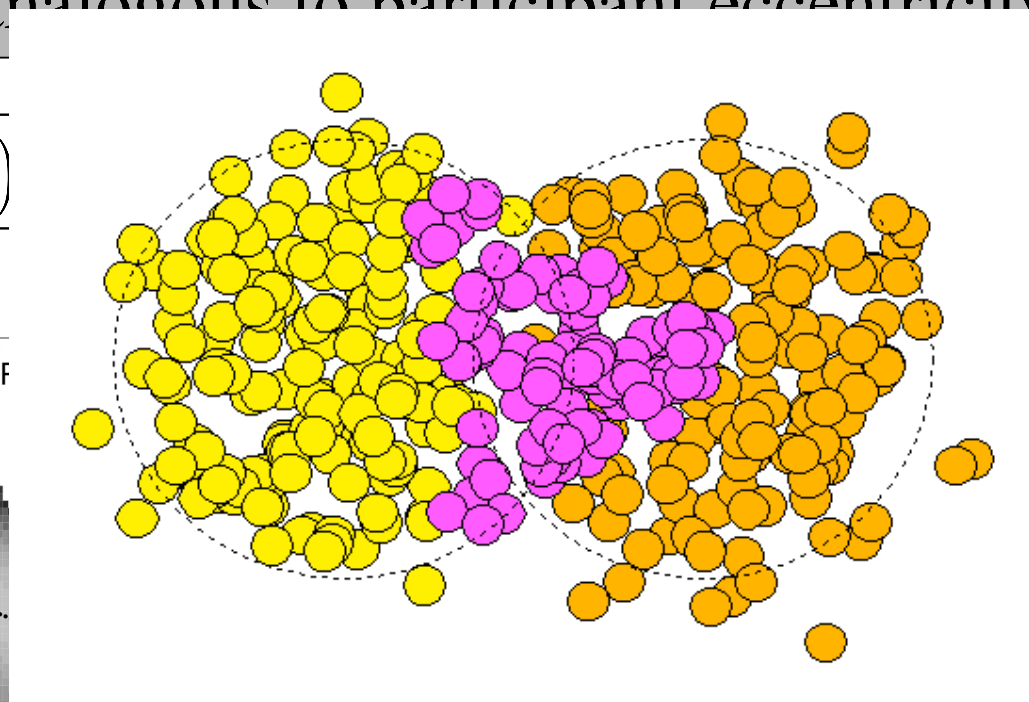
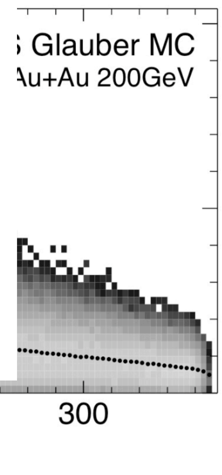
$$\varepsilon = \frac{\sqrt{\left\langle\left(r^2\cos(2\phi)\right)\ldots}}{\ldots}$$

$$\ldots\left\langle\left(r^2\sin(3\phi)\right)\right\rangle^2$$

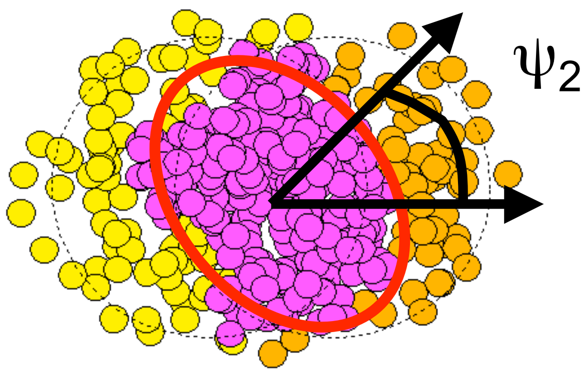


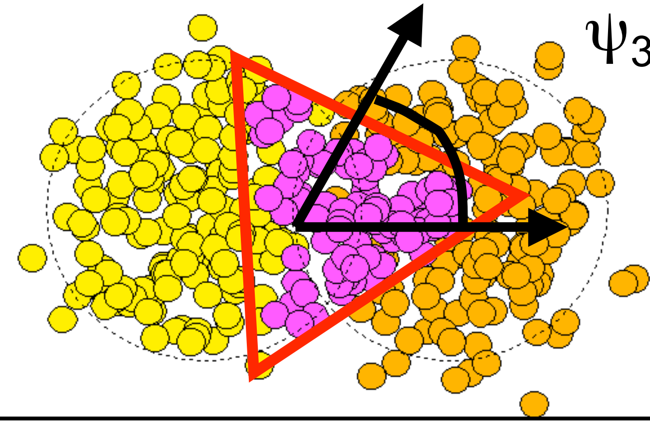


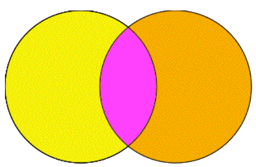


BA, G.Roland, PRC81, 054905 (2010)

Triangular flow



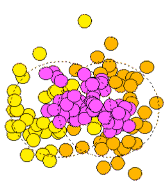




$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1+\sum 2v_n \cos\left(n(\phi-\psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi-\psi_R)\right)\right\rangle$$

$$v_3 = 0$$



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1+\sum 2v_n \cos\left(n(\phi-\psi_n)\right)\right)$$

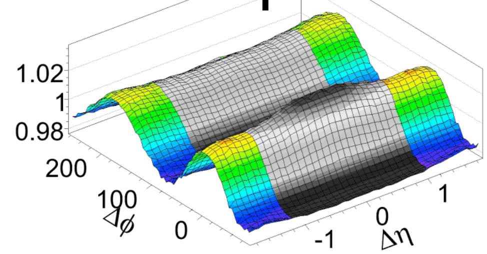
$$v_2 = \left\langle \cos\left(2(\phi-\psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi-\psi_3)\right)\right\rangle$$

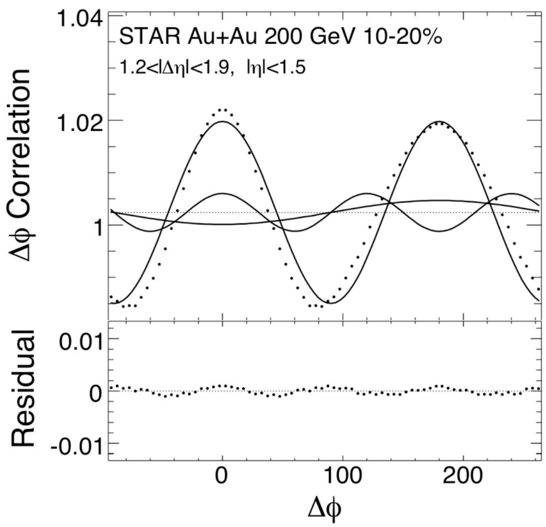
BA, G.Roland, PRC81, 054905 (2010)

Correlations at large $\Delta\eta$

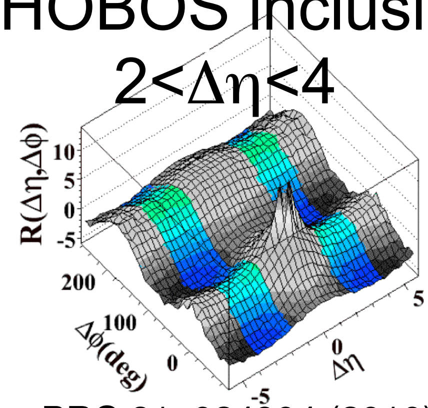
STAR inclusive
$1.2<\Delta\eta<1.9$



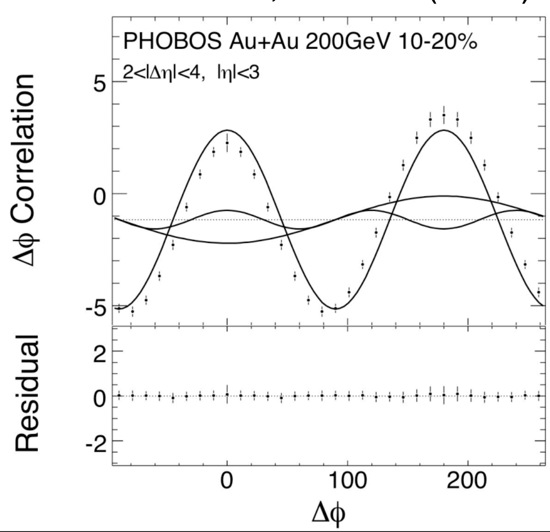
arXiv:0806.0513



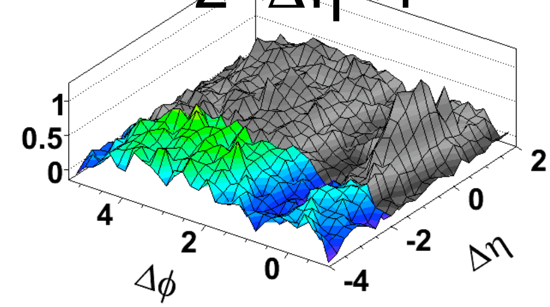
PHOBOS inclusive
$2<\Delta\eta<4$



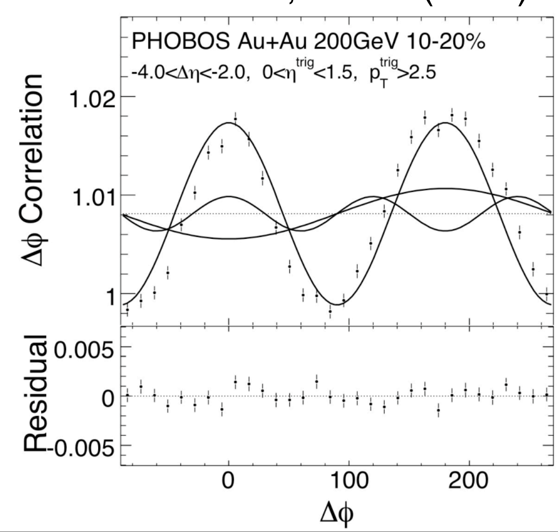
PRC 81, 024904 (2010)



PHOBOS p_T^{trig}>2GeV
$2<\Delta\eta<4$



PRL 104, 06230 (2010)

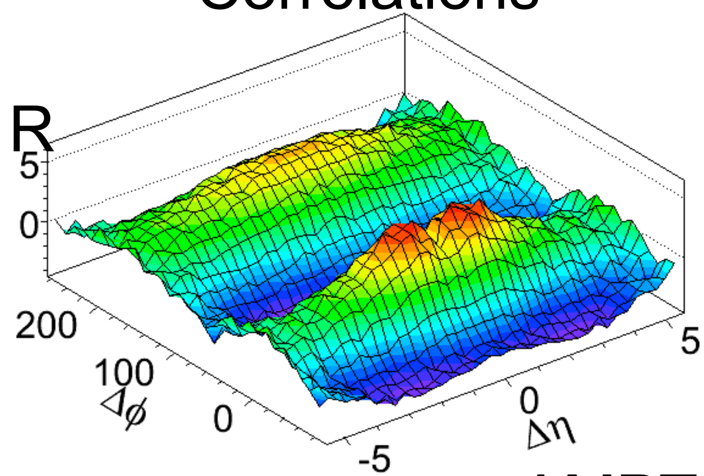


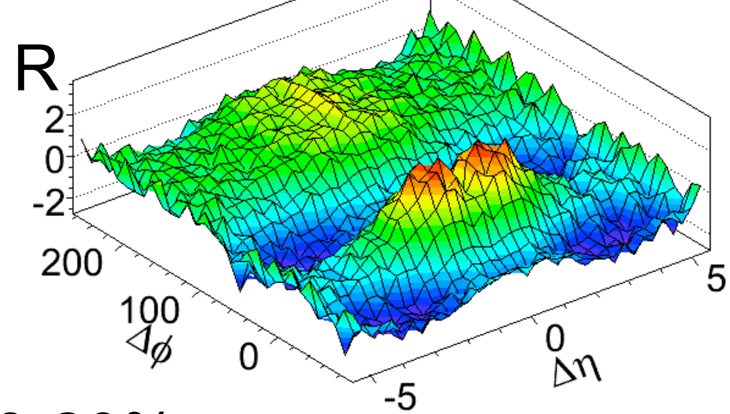
Long range correlations are well described by 3 Fourier Components.

BA, G.Roland, PRC81, 054905 (2010)

AMPT Model

AMPT model: Glauber initial conditions, collective flow



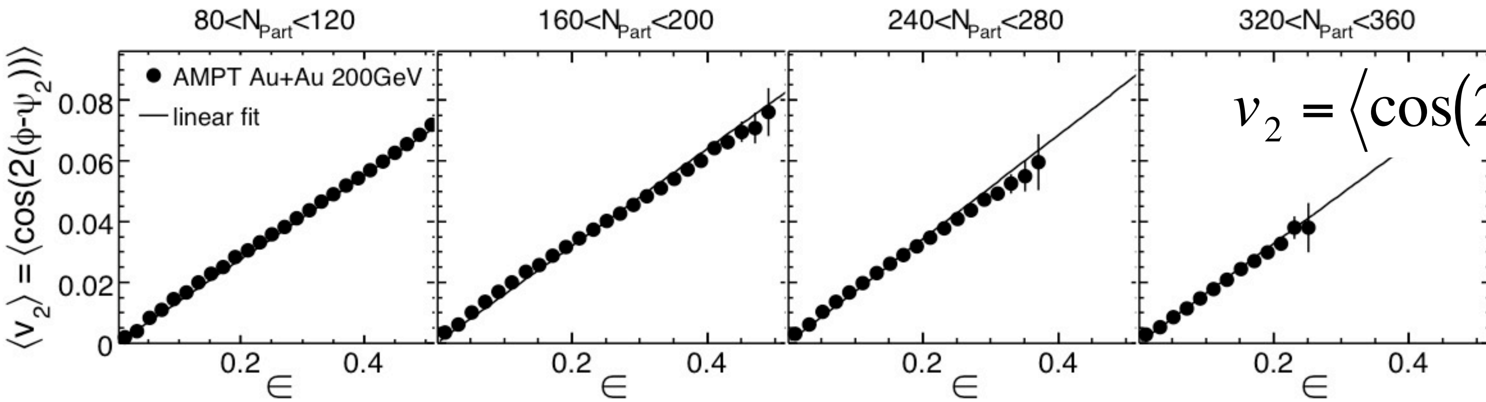


AMPT Au+Au 0-20%

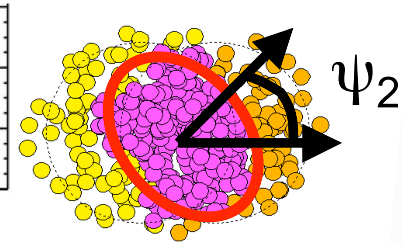
AMPT model also produces similar correlation structures that extend out to long range in Δη.

Lin et. al. PRC72, 064901 (2005)
Ma et. Al. PLB641 362 (2006)

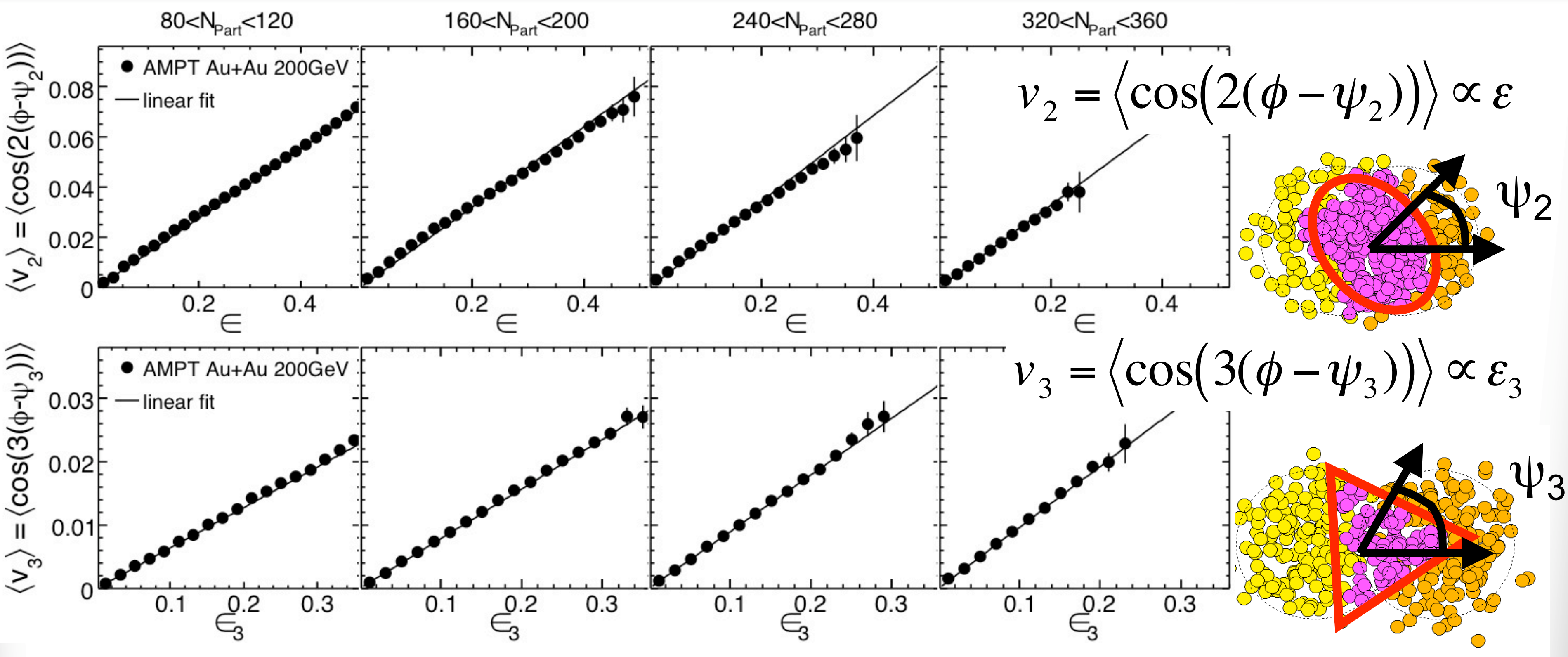
Elliptic flow in AMPT



$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right) \right\rangle \propto \varepsilon$$



Triangular flow in AMPT

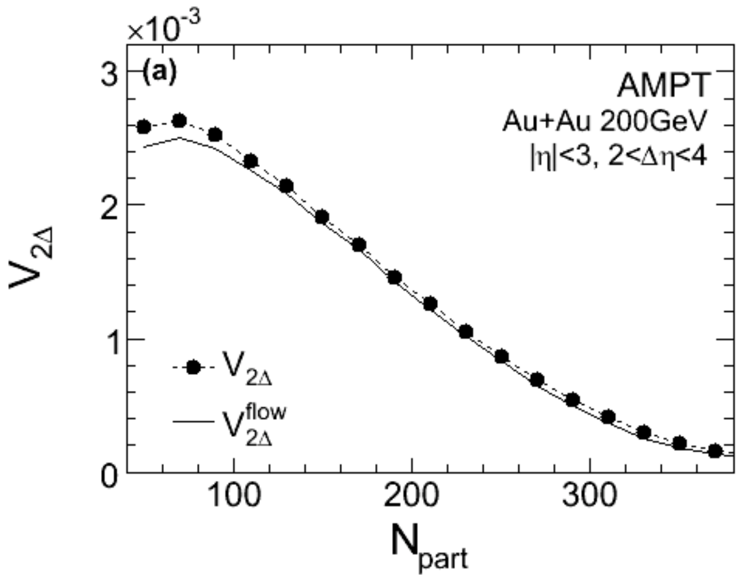


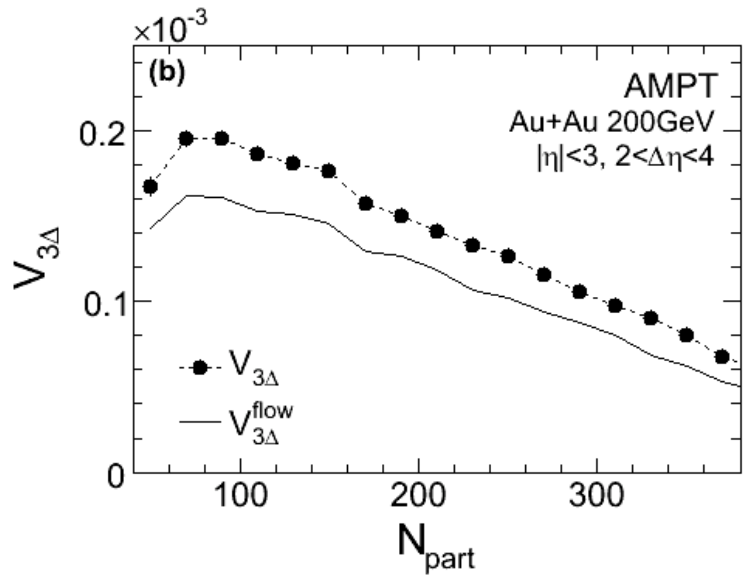
Triangularity leads to triangular flow in AMPT.

BA, G.Roland, PRC81, 054905 (2010)

Flow and correlations in AMPT

$$\frac{dN}{d\Delta\phi} = \frac{N}{2\pi}\left(1 + \sum 2\mathbf{V}_{n\Delta}\cos\left(n\Delta\phi\right)\right) \qquad \mathbf{V}_{\mathbf{n\Delta}}^{\mathbf{flow}} \sim \int v_n(\eta) \times v_n(\eta + \Delta\eta)\, d\eta$$





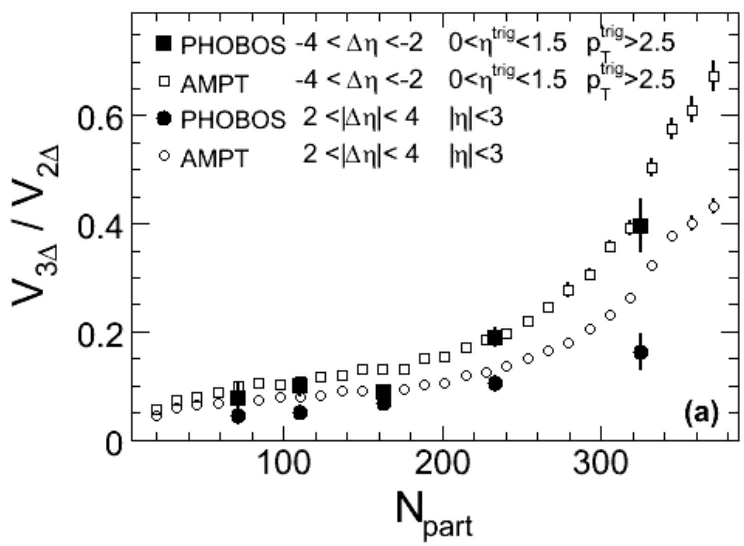
$$\mathbf{V}_{\mathbf{3\Delta}} = \left\langle \cos\left(3(\phi_1 - \phi_2)\right)\right\rangle$$

$$\mathbf{V}_{\mathbf{3\Delta}}^{\mathbf{flow}} = \left\langle \cos\left(3(\phi_1 - \psi_3)\right)\right\rangle\left\langle \cos\left(3(\phi_2 - \psi_3)\right)\right\rangle$$

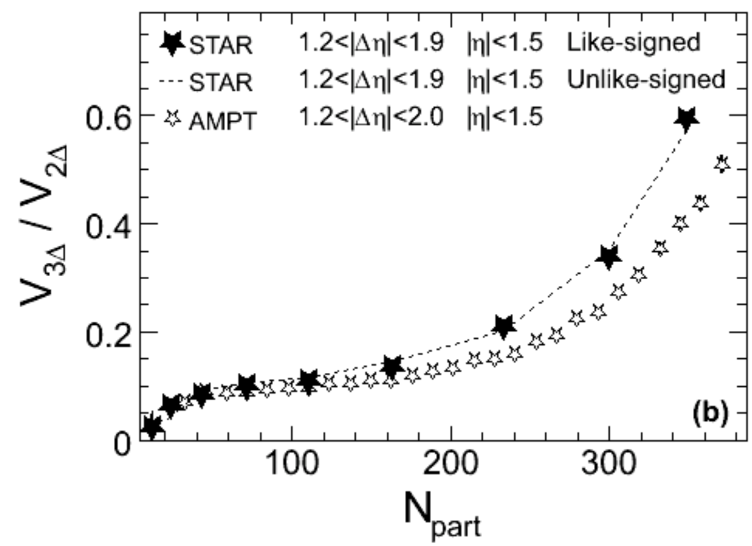
BA, G.Roland, PRC81, 054905 (2010)

Triangular flow in data

PHOBOS



STAR



The ratio of triangular flow to elliptic flow qualitatively agree between data and AMPT.

STAR arXiv:0806.0513

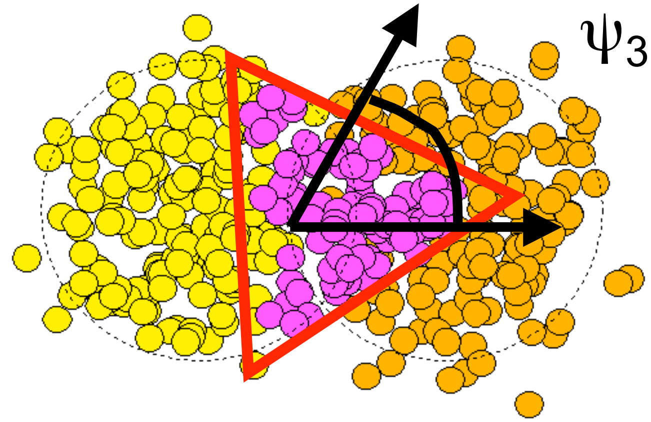
PHOBOS PRC 81, 024904 (2010)

PHOBOS PRL 104, 06230 (2010)

BA, G.Roland, PRC81, 054905 (2010)

Summary

- Fluctuations in MC Glauber leads to finite “participant triangularity.”
- In AMPT model, large triangular flow signal observed correlated with initial triangularity:



$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle \propto \varepsilon_3$$

- Ridge and broad away side in AMPT have dominant contribution from triangular flow.
- Fourier decomposition of long range azimuthal correlations in AMPT and data show qualitative agreement as a function of centrality and momentum.

BA, G.Roland, PRC81, 054905 (2010)

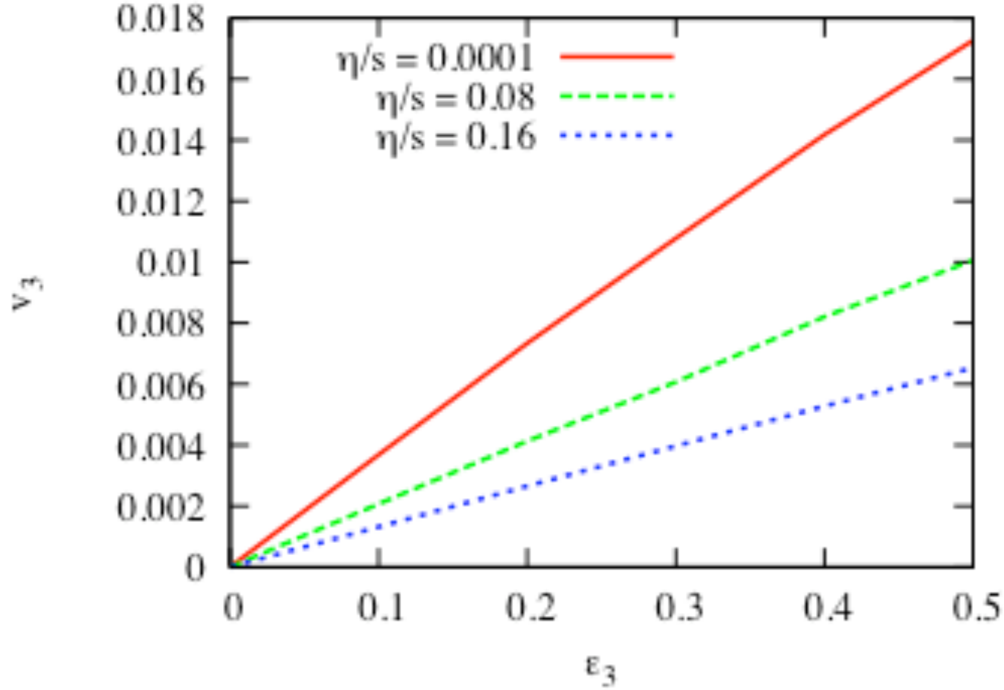
Conclusions

- Initial geometry fluctuations can explain the ridge and broad away side.
- The correct language to use for these structure is that of flow.

$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right) \right\rangle \propto \varepsilon$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right) \right\rangle \propto \varepsilon_3$$

Future



Triangular flow is a new handle on the initial geometry and the hydrodynamic expansion of the medium.

Luzum, Ollitrault Private communication

Backups

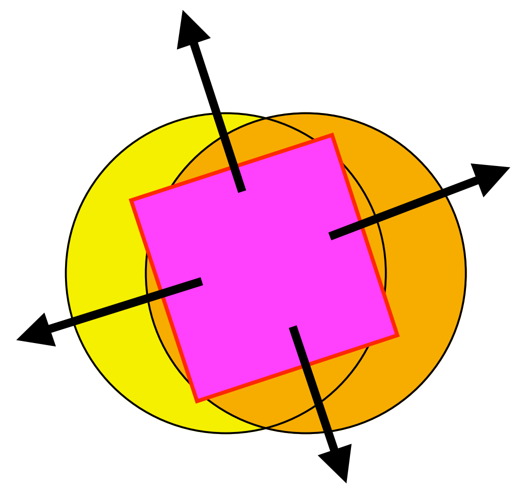
Future: v_4

Naïve generalization:

$$\varepsilon_4 = \frac{\sqrt{\left\langle\left(r^2\cos(4\phi)\right\rangle^2 + \left\langle\left(r^2\sin(4\phi)\right\rangle^2}}{\left\langle r^2\right\rangle}$$

$$\psi_4 = \frac{\operatorname{atan2}\left(\left\langle r^2\sin\left(4\phi_{\text{part}}\right)\right\rangle,\left\langle r^2\cos\left(4\phi_{\text{part}}\right)\right\rangle\right)+\pi}{4}$$

$$v_4 = \left\langle\cos\left(4(\phi-\psi_4)\right)\right\rangle \propto \varepsilon_4$$



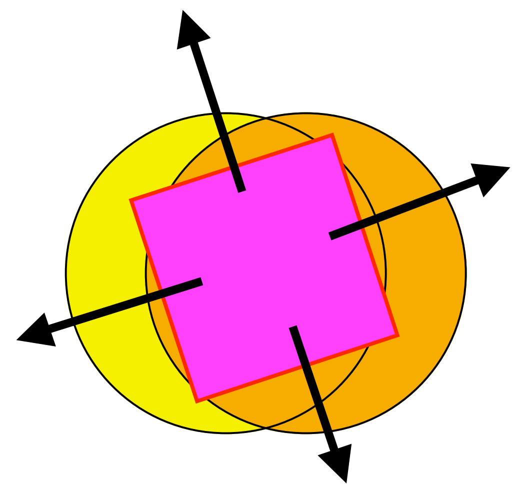
Future: v_4

Naïve generalization:

$$\varepsilon_4 = \frac{\sqrt{\left\langle \left(r^2 \cos(4\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(4\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

$$\psi_4 = \frac{\mathrm{atan2}\left(\left\langle r^2 \sin\left(4\phi_{\mathrm{part}}\right)\right\rangle, \left\langle r^2 \cos\left(4\phi_{\mathrm{part}}\right)\right\rangle\right) + \pi}{4}$$

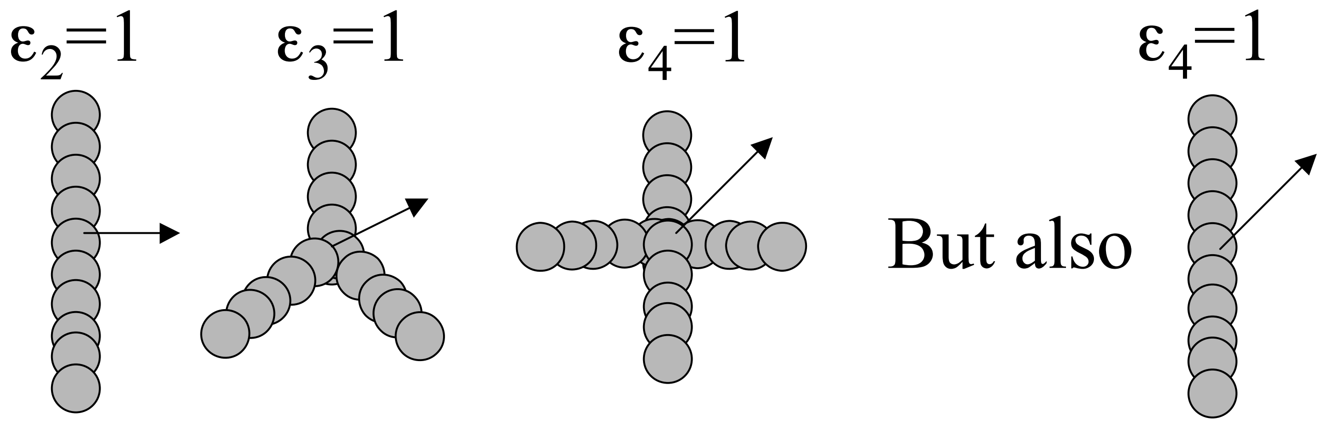
$$v_4 = \left\langle \cos\left(4(\phi - \psi_4)\right)\right\rangle \propto \varepsilon_4$$



Future: v_4

4 is not a prime number.

1. Need a better definition for "quadrangularity"

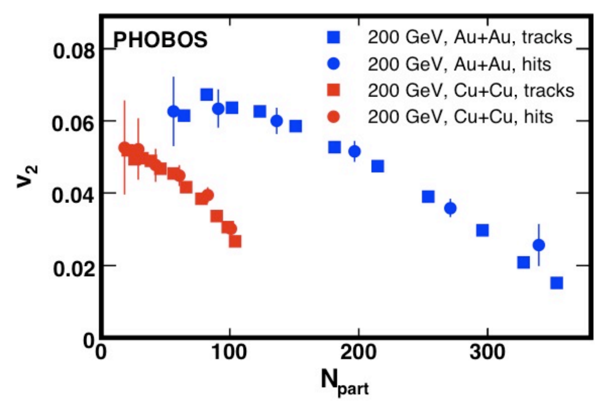


2. Eccentricity also leads to v_4. (Ollitrault PLB642 227)

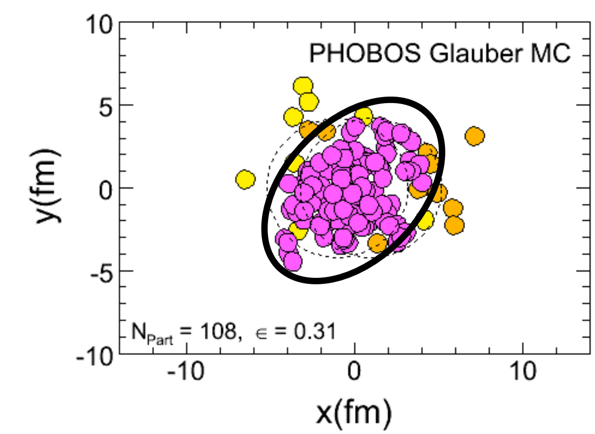
$$v_4(p_t) = \frac{(V_2 u_{\max})^2}{2T^2}(p_t - m_t v_{\max})^2 + \frac{V_4 u_{\max}}{T}(p_t - m_t v_{\max}) \,.$$

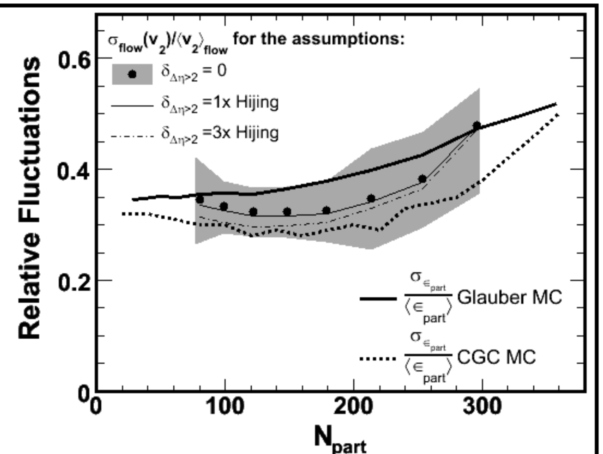
Initial geometry fluctuations

A consistent picture

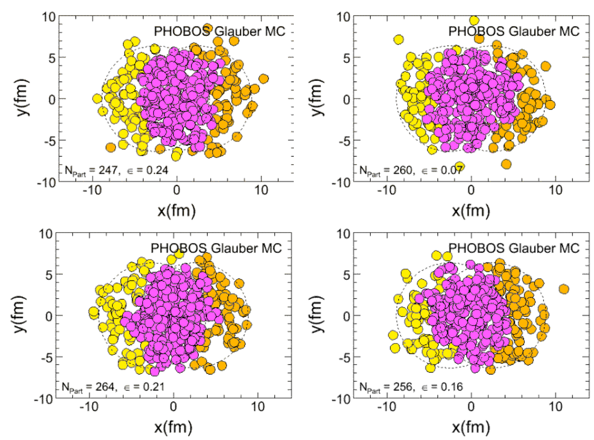


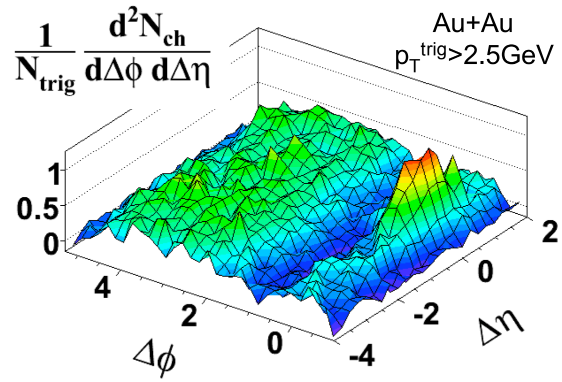
PHOBOS PRL 98, 242302 (2007)



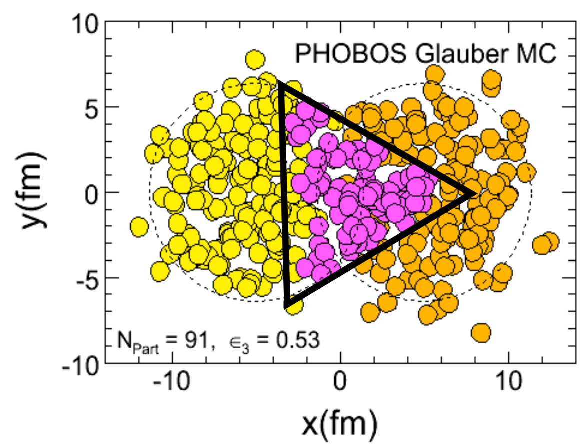


PHOBOS PRC81, 034915 (2010)



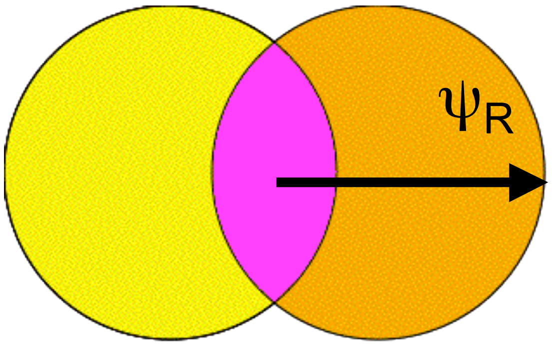


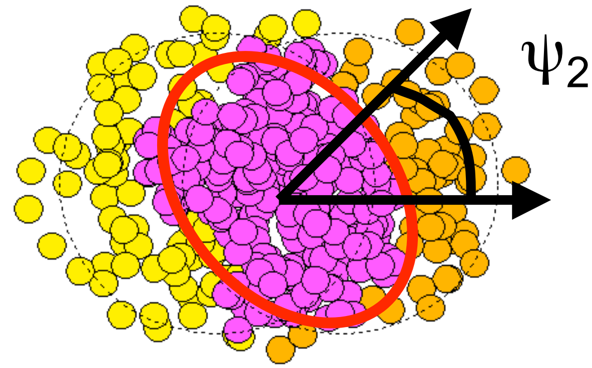
PHOBOS PRL 104, 06230 (2010)



BA, G.Roland, PRC81, 054905 (2010)

Two different pictures





$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

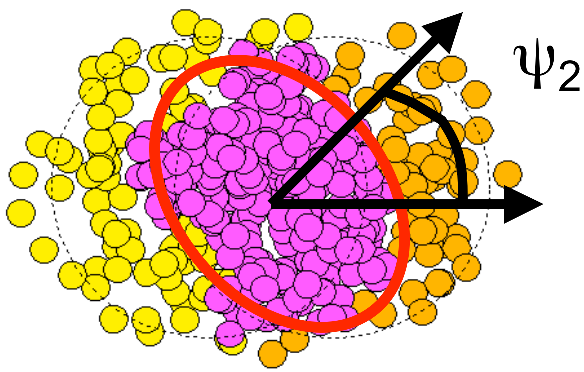
$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

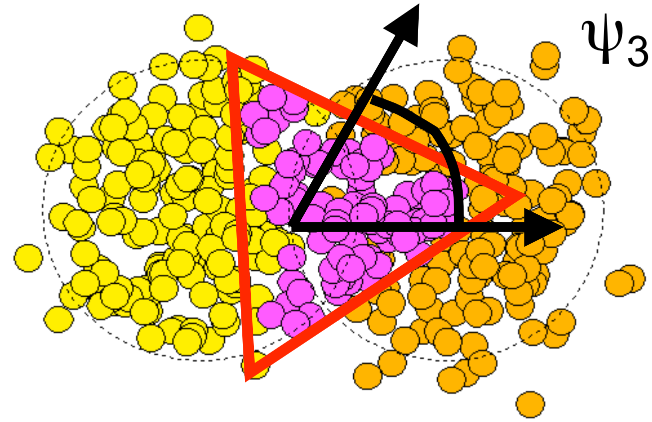
$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

PHOBOS PRL 98, 242302 (2007)

Triangular flow





$$\psi_2 = \frac{\operatorname{atan2}\left(\left\langle r^2 \sin\left(2\phi_{\text{part}}\right)\right\rangle, \left\langle r^2 \cos\left(2\phi_{\text{part}}\right)\right\rangle\right) + \pi}{2}$$

$$\psi_3 = \frac{\operatorname{atan2}\left(\left\langle r^2 \sin\left(3\phi_{\text{part}}\right)\right\rangle, \left\langle r^2 \cos\left(3\phi_{\text{part}}\right)\right\rangle\right) + \pi}{3}$$

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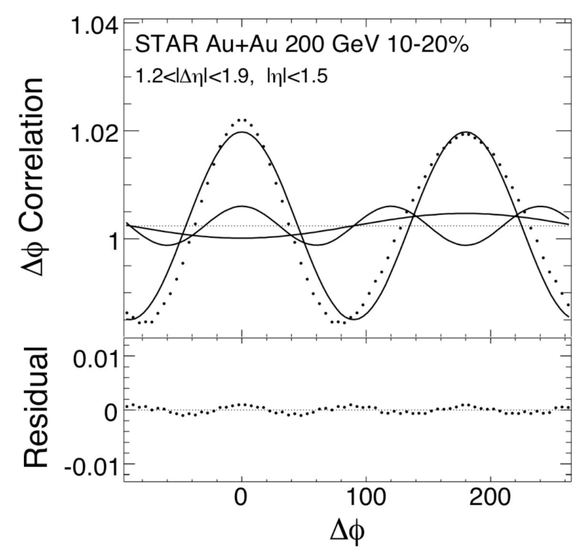
Phases

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

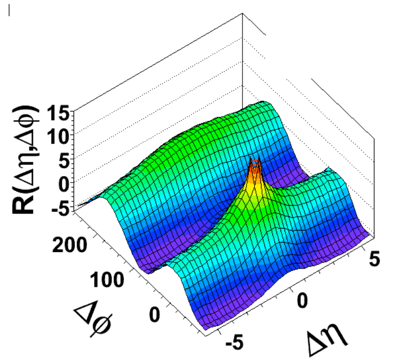
$$= \frac{N}{2\pi}\left(1 + \ldots + 2v_2 \cos\left(2(\phi - \psi_2)\right) + 2v_3 \cos\left(3(\phi - \psi_3)\right) + \ldots\right)$$

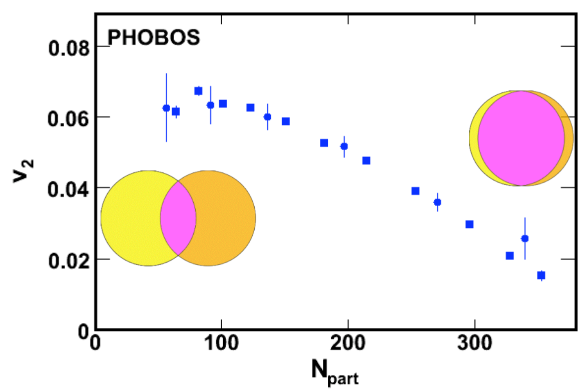
$$\frac{\mathrm{d}N^{\mathrm{pairs}}}{\mathrm{d}\Delta\phi} = \frac{N^{\mathrm{pairs}}}{2\pi}\left(1 + \ldots + 2v_2^2 \cos\left(2\Delta\phi\right) + 2v_3^2 \cos\left(3\Delta\phi\right) + \ldots\right)$$

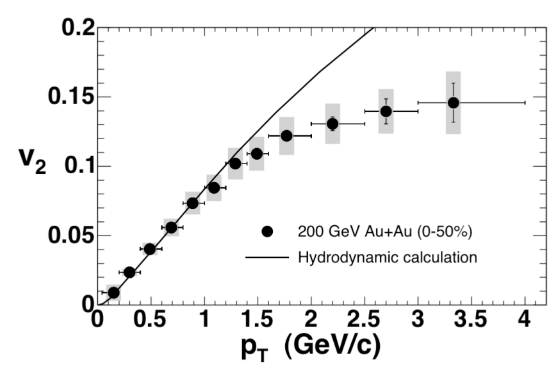


Second Fourier coefficient

- Why do we believe it is collective flow?
  - Large!
  - Present at large $\Delta\eta$: early times
  - Connection to initial geometry
    - i.e. centrality dependence
  - p_T dependence
  - Also $v_2\{4\}$, v_2 fluctuations and $v_2^2(\eta_1,\eta_2)$

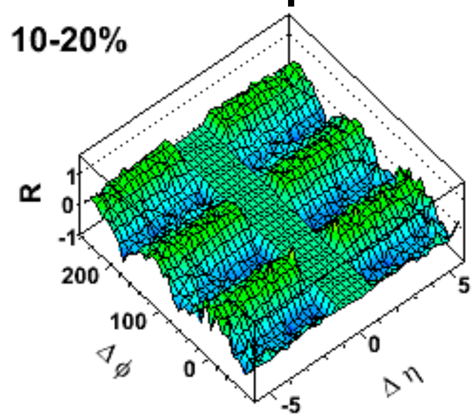


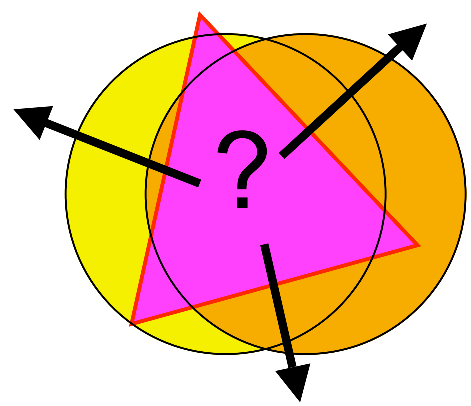




Third Fourier coefficient

- Why should we believe it is collective flow?
  - Large!
  - Present at large $\Delta\eta$: early times
  - Connection to initial geometry
    - i.e. centrality dependence
  - p_T dependence
  - Also three particle correlations

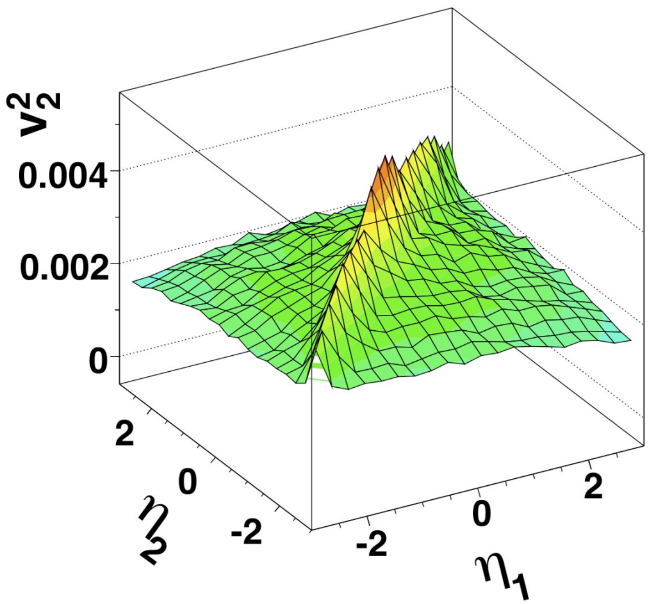




BA, G.Roland, PRC81, 054905 (2010)

A side note: flow vs. non–flow

$$v_2^2(\eta_1,\eta_2) = \underbrace{v_2(\eta_1)\times v_2(\eta_2)}_{\text{flow}} + \underbrace{\delta(\eta_1,\eta_2)}_{\text{non-flow}}$$



A side note: flow vs. non-flow

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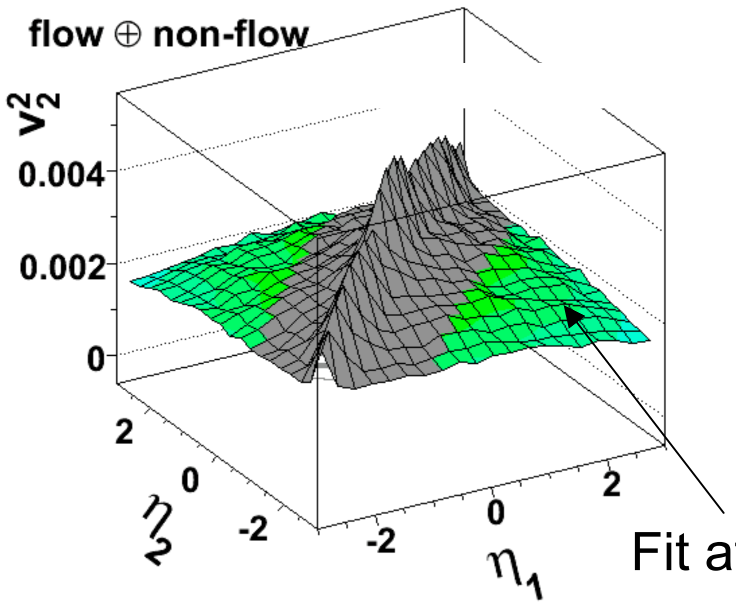
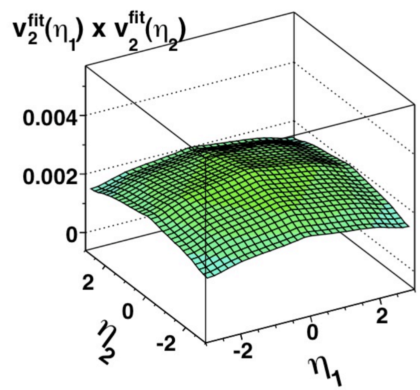
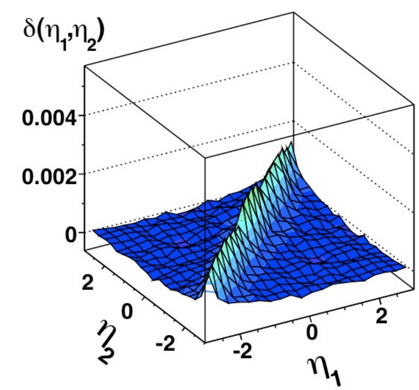
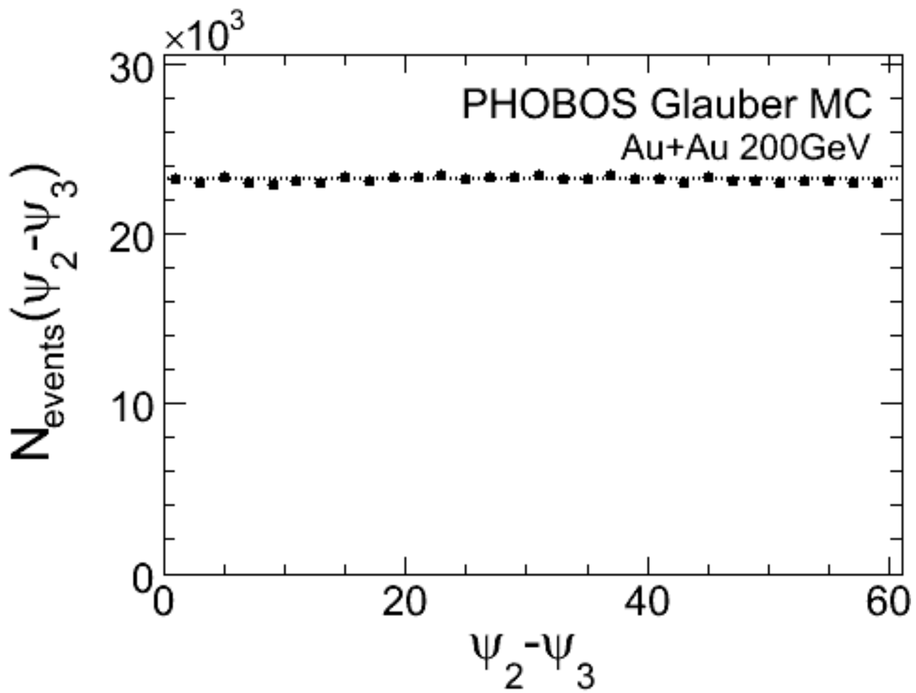


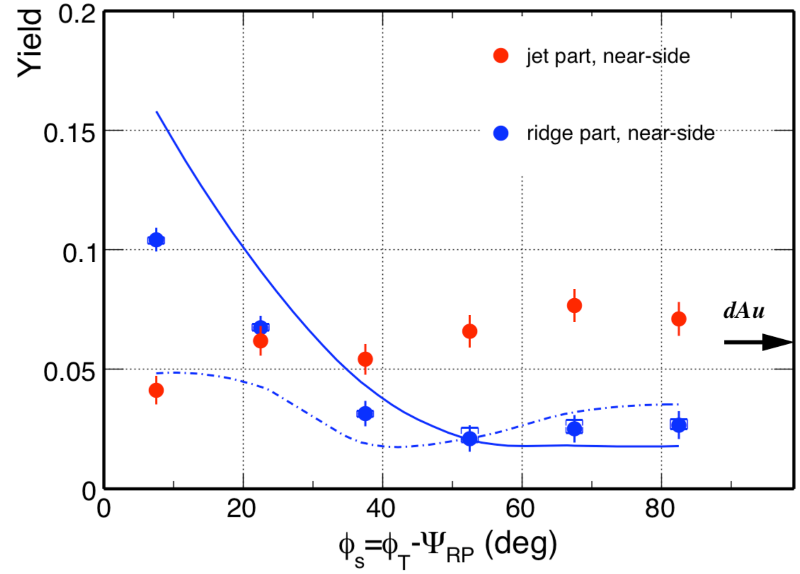


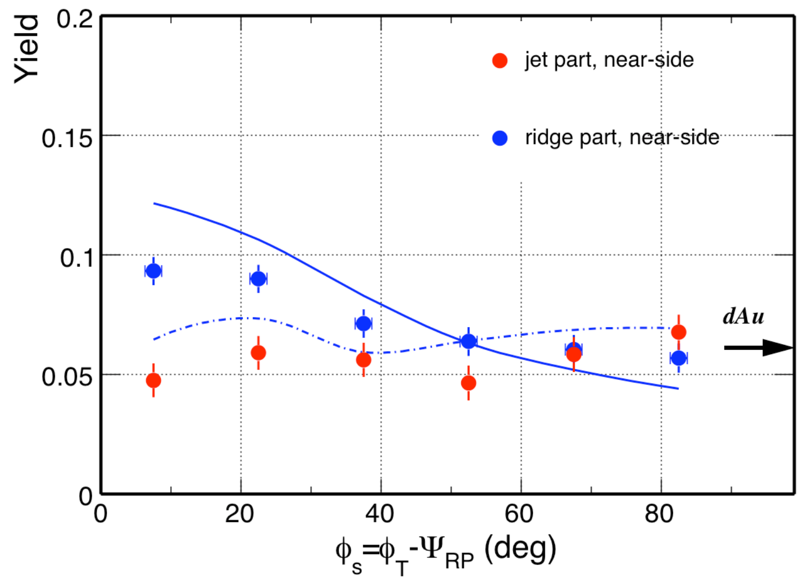


The best approach may be to assume non-flow to be negligible at long ranges.

Ridge vs. ψ_2

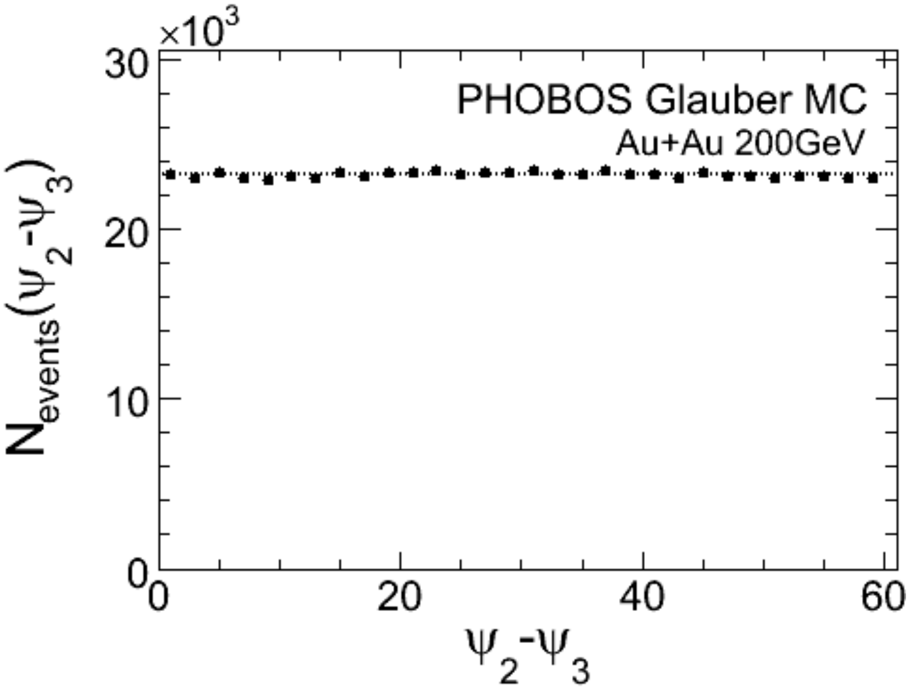


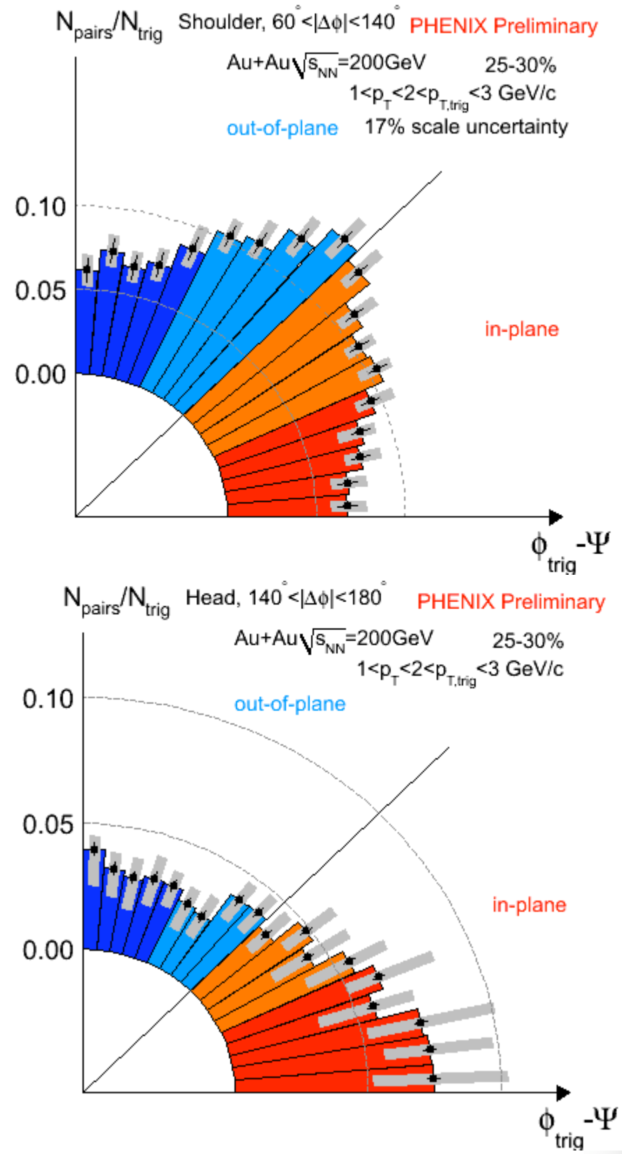




STAR Preliminary

Shoulder vs. ψ_2

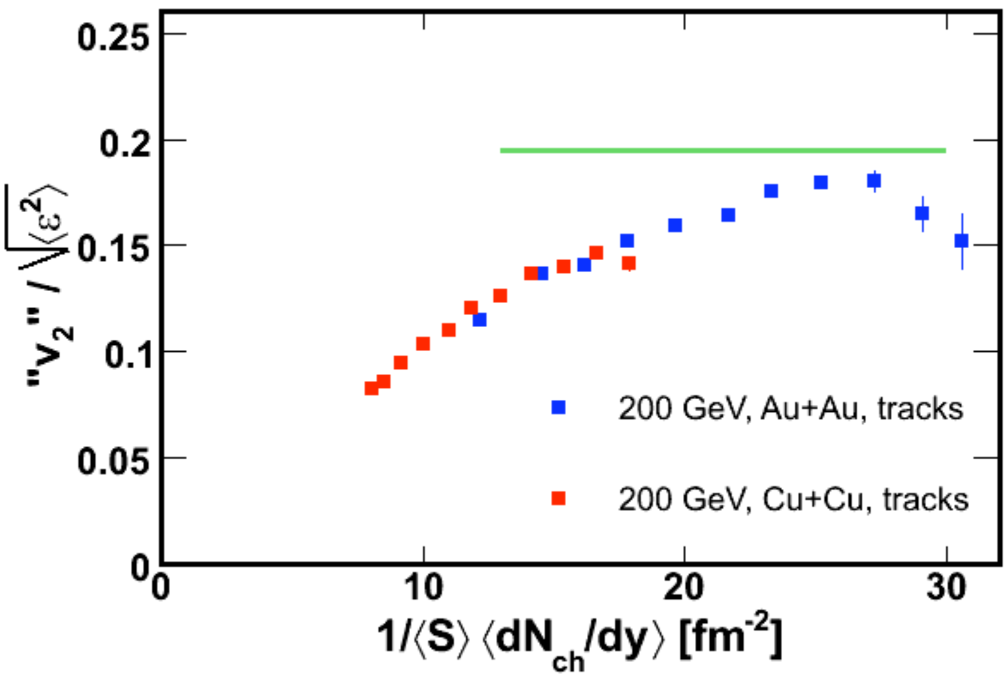




Phenix Preliminary

Implications for <v_2>

Conclusions for elliptic flow due to fluctuations:
v_2 was over-estimated. ε was under-estimated.



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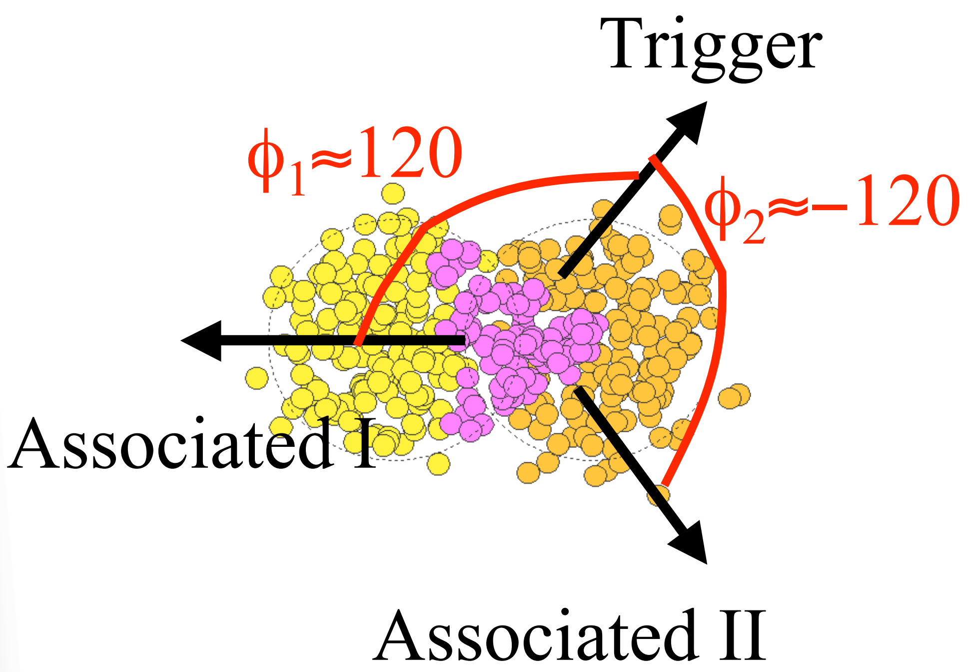
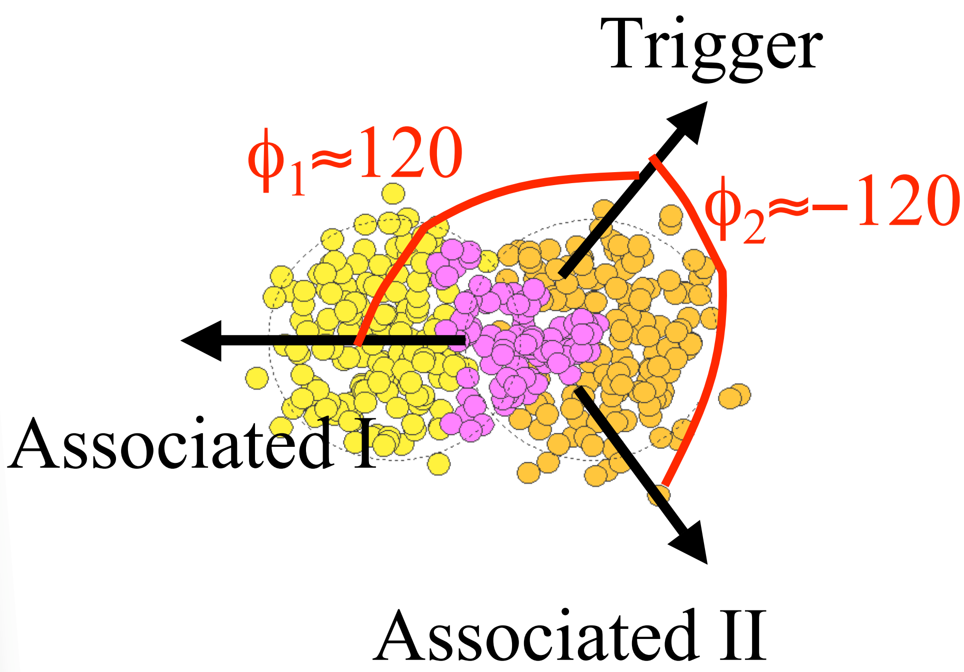
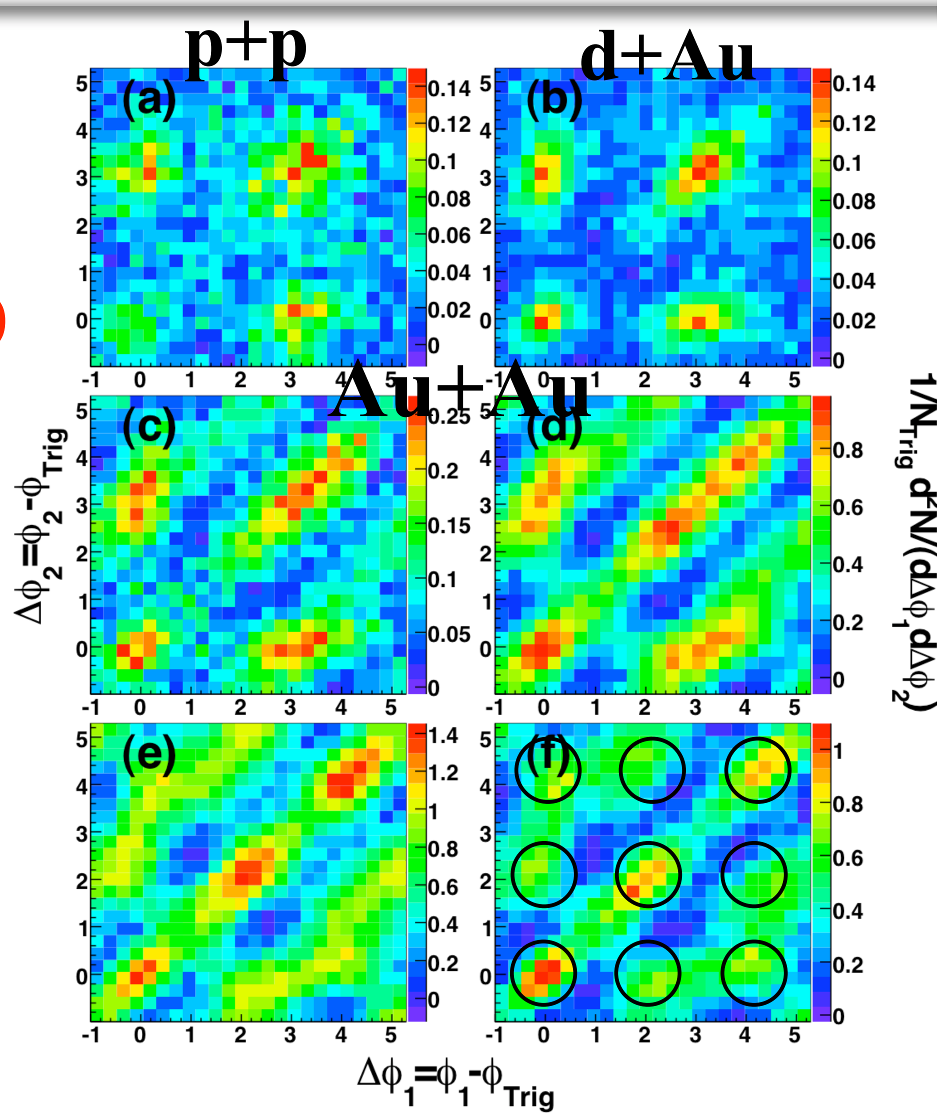
Three particle correlation I



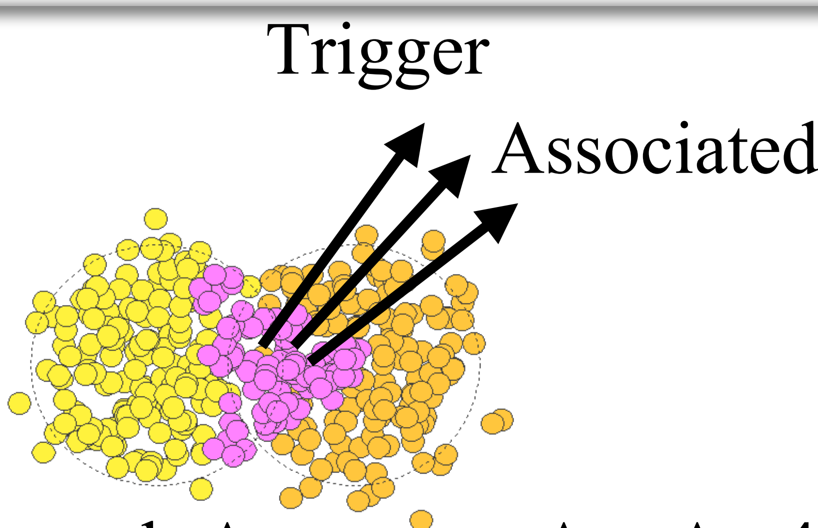
Three particle correlation I

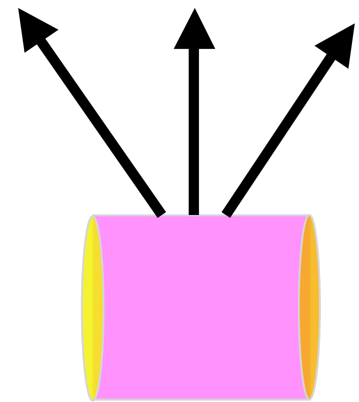




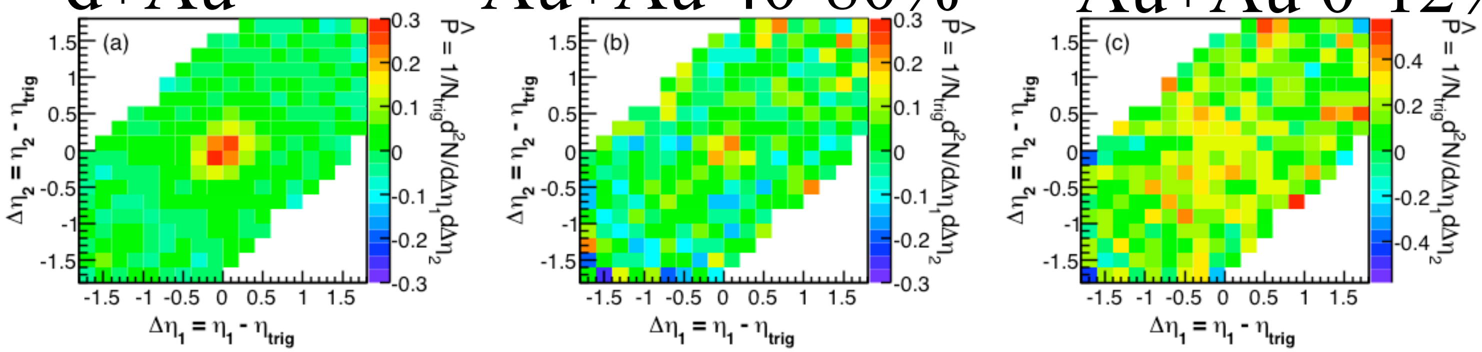
STAR

Three particle correlation II





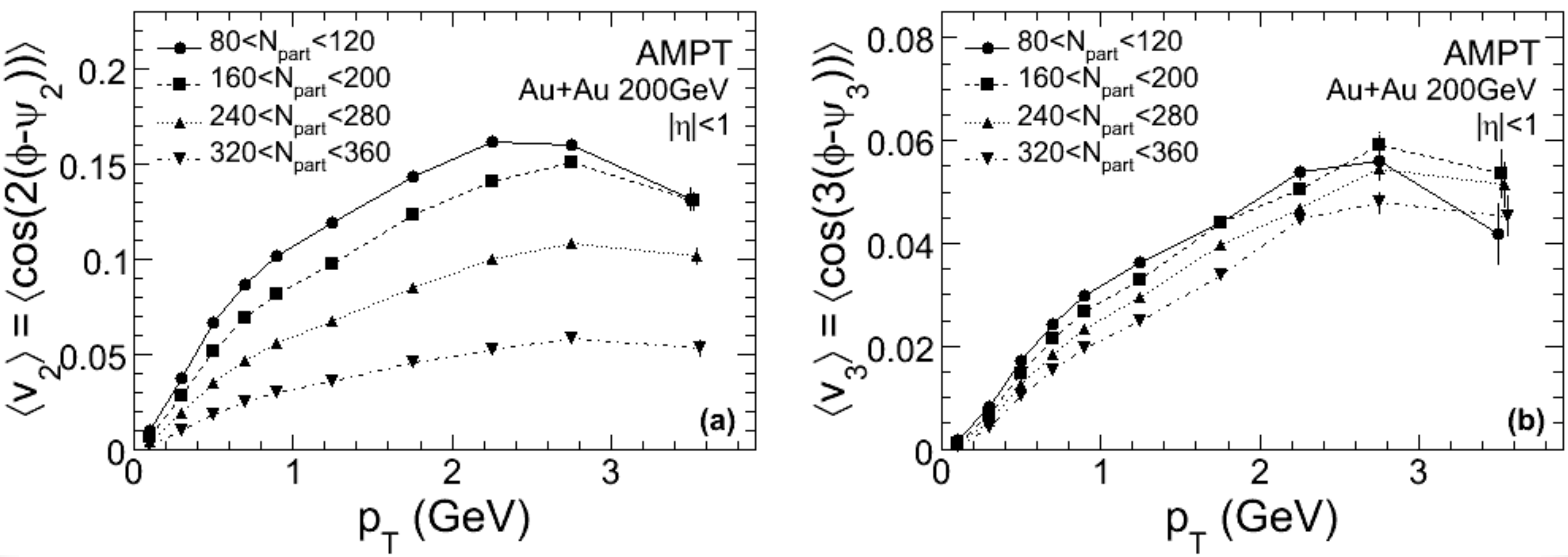
d+Au Au+Au 40-80% Au+Au 0-12%



No structure is observed consistent with triangular flow

STAR

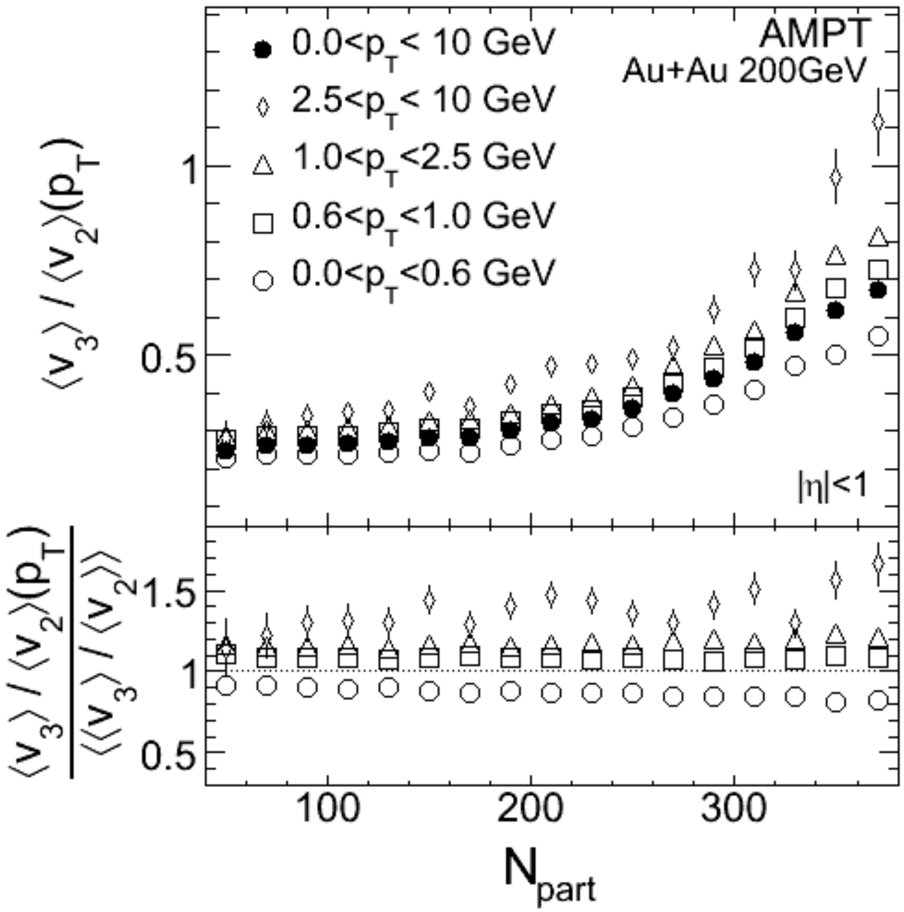
p_T dependence



$v_2(p_T)$ and $v_3(p_T)$ show similar gross features in AMPT

BA, G.Roland, PRC81, 054905 (2010)

p_T dependence



v_3/v_2 increases with centrality and p_T

This explains why the ridge was observed at high p_T correlations in central collisions

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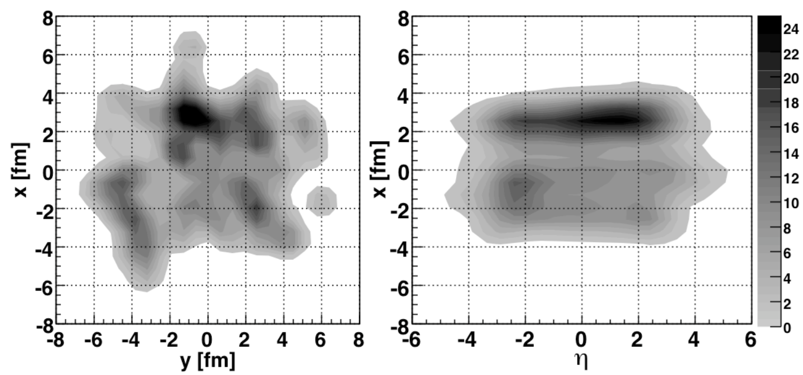
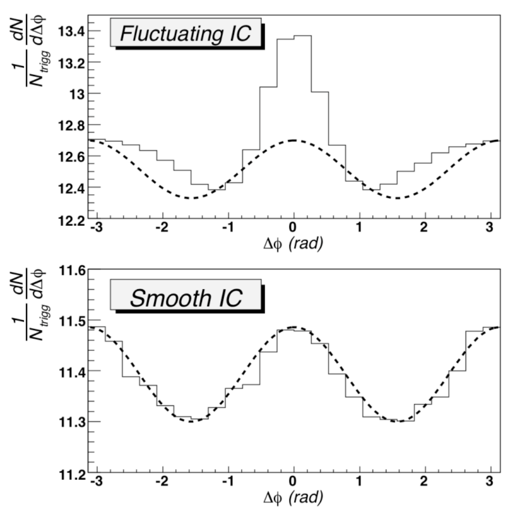
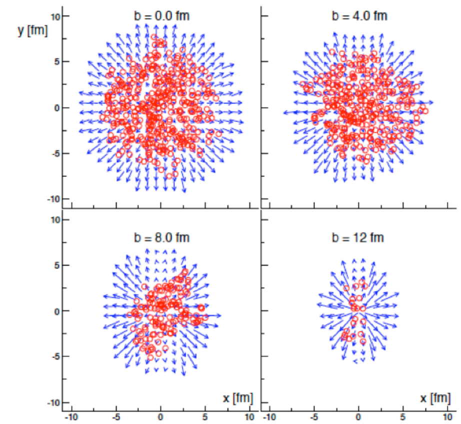
Initial geometry fluctuations

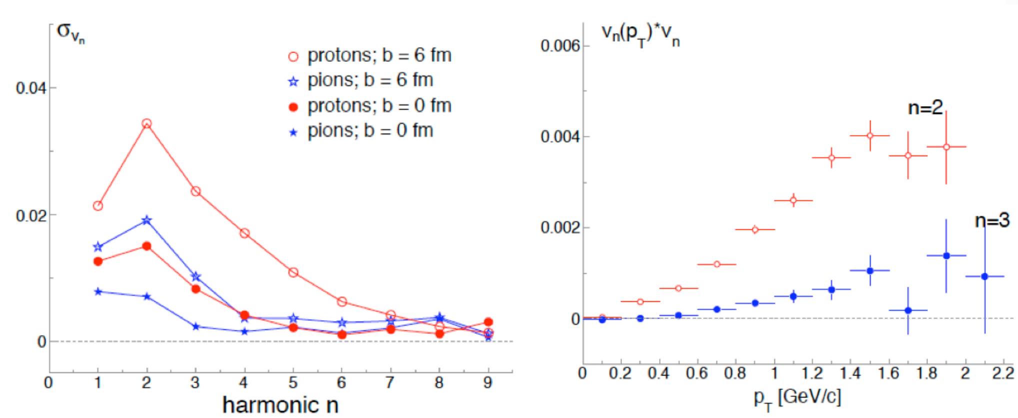
J. Takahashi et al.





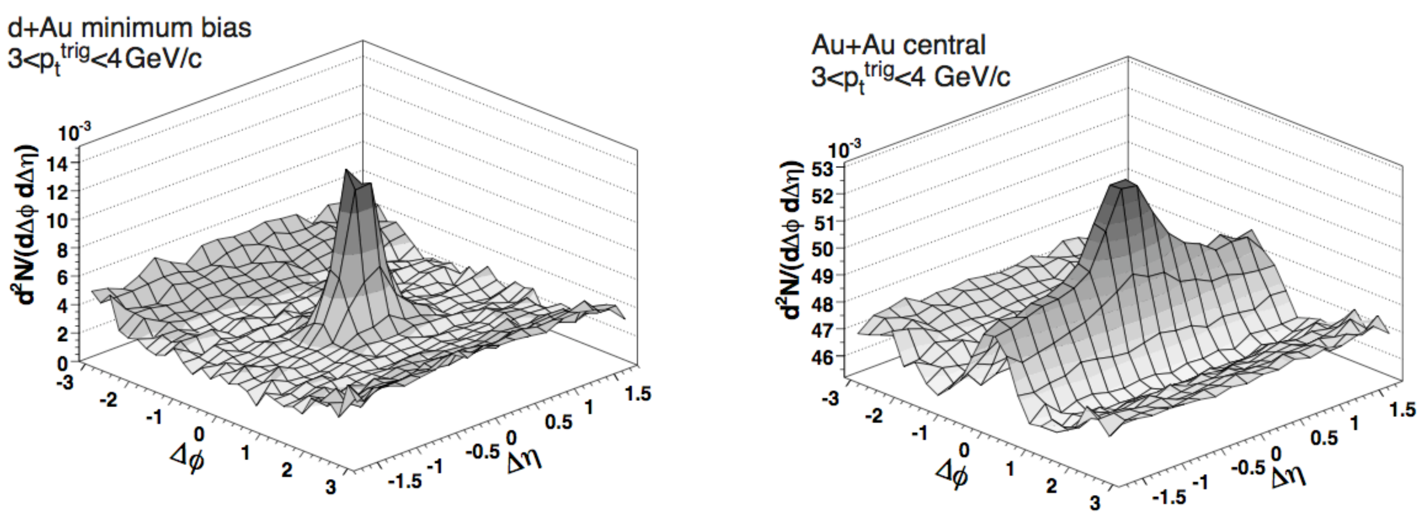
P. Sorensen





Ridge and broad-away side

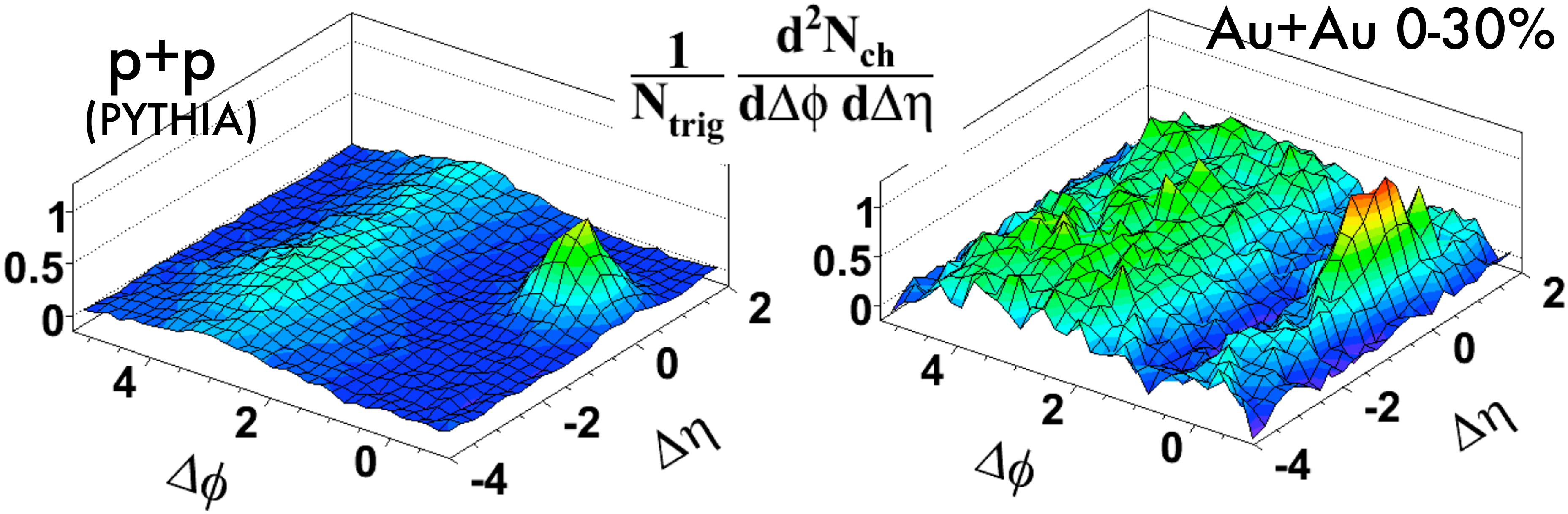
Two particle correlations with high p_T trigger, $\Delta\eta<2$
A ridge and broad side observed in comparison to p+p.



STAR PRC80 064912 (2009)

Ridge and broad-away side

Also at $2<\Delta\eta<4$

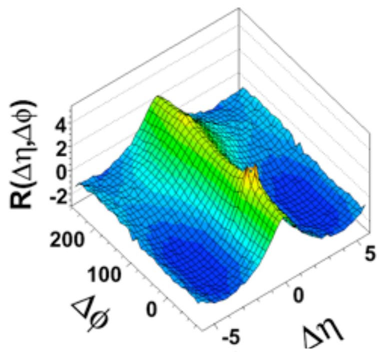


PHOBOS PRL 104, 06230 (2010)

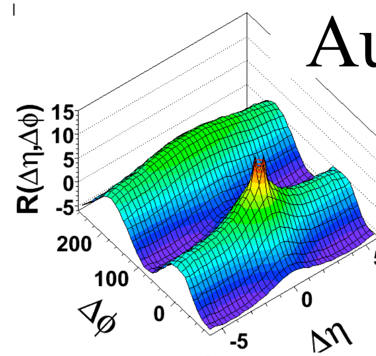
Ridge and broad-away side

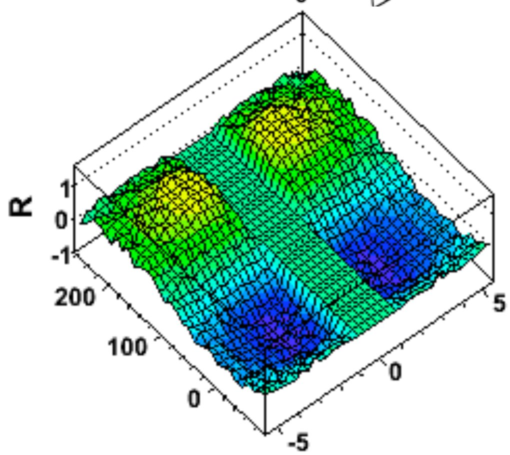
Actually:
Ridge and broad away side at low p_T out to $\Delta\eta$=5.5

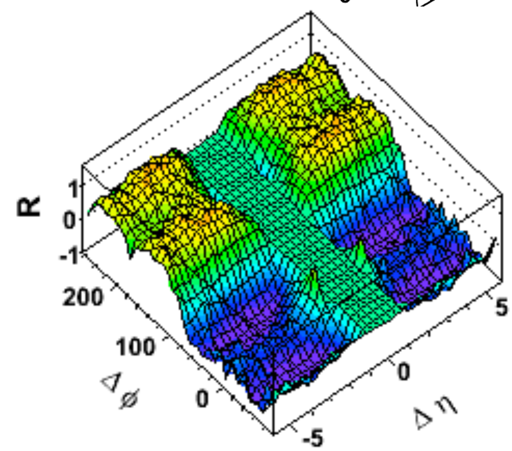
p+p



Au+Au 10-20%







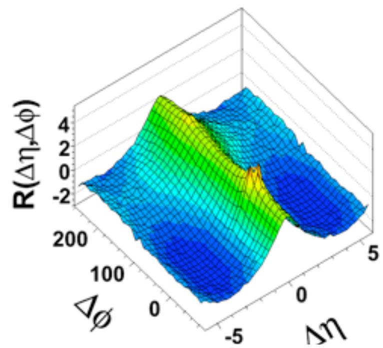
Taking out all $V_{2\Delta}$

PHOBOS PRC 81, 024904 (2010)

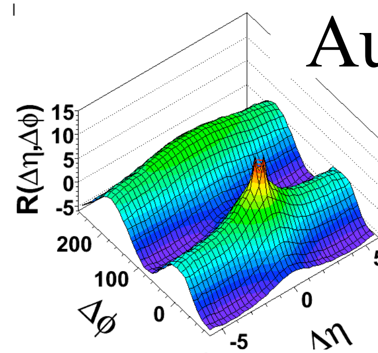
Ridge and broad-away side

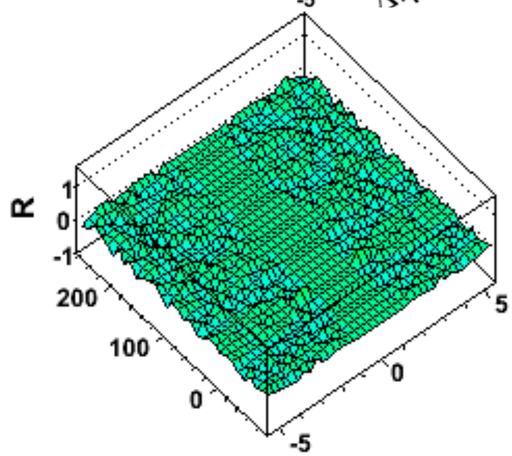
Actually:
Ridge and broad away side at low p_T out to $\Delta\eta$=5.5

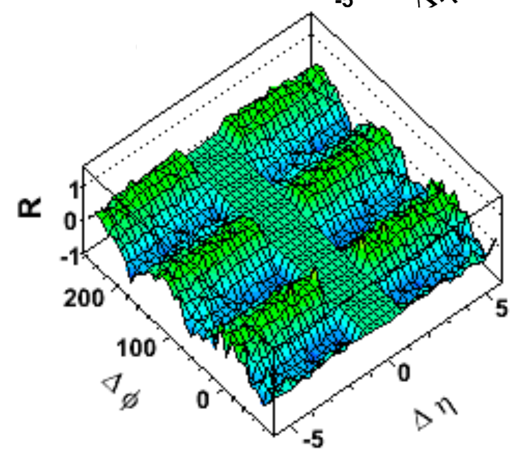
p+p



Au+Au 10-20%







Taking out all $V_{1\Delta}$ and $V_{2\Delta}$

PHOBOS PRC 81, 024904 (2010)